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Ambient Water Quality Criteria for Copper

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Section 304(A) of the Clean Water Act [33 U.S.C. 1314(A)], requires EPA to publish and periodically update water quality criteria. These criteria are to reflect the latest scientific knowledge on the identifiable effects of pollutants on public health and welfare, aquatic life, and recreation. This report presents water quality criteria for Copper. It presents concentration criteria for the protection of freshwater and saltwater aquatic life. It presents 'safe' concentrations for humans, and in the case of suspect or proven carcinogens, gives various levels of incremental cancer risk. A Section 304(A) water quality criterion is a qualitative or quantitative estimate of the concentration of a water constituent or pollutant in ambient waters which, when not exceeded, will ensure a water quality sufficient to protect a specified water use. Under the Act a criterion is a scientific entity, based solely on data and scientific judgment. It does not reflect considerations of economic or technological feasibility nor is it a water quality standard and in itself has no regulatory effect.

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COPPER

Prepared By
U.S. ENVIRONMENTAL PROTECTION AGENCY

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FOREWORD

Section 304 (a)(1) of the Clean Water Act of 1977 (P.L. 95-217), requires the Administrator of the Environmental Protection Agency to publish criteria for water quality accurately reflecting the latest scientific knowledge on the kind and extent of all identifiable effects on health and welfare which may be expected from the presence of pollutants in any body of water, including ground water. Proposed water quality criteria for the 65 toxic pollutants listed under section 307 (a)(1) of the Clean Water Act were developed and a notice of their availability was published for public comment on March 15, 1979 (44 FR 15926), July 25, 1979 (44 FR 43660), and October 1, 1979 (44 FR 56628). This document is a revision of those proposed criteria based upon a consideration of comments received from other Federal Agencies, State agencies, special interest groups, and individual scientists. The criteria contained in this document replace any previously published EPA criteria for the 65 pollutants. This criterion document is also published in satisifaction of paragraph 11 of the Settlement Agreement in Natural Resources Defense Council, et. al. vs. Train, 8 ERC 2120 (D.D.C. 1976), modified, 12 ERC 1833 (D.D.C. 1979).

The term "water quality criteria" is used in two sections of the Clean Water Act, section 304 (a)(1) and section 303 (c)(2). The term has a different program impact in each section. In section 304, the term represents a non-regulatory, scientific assessment of ecological effects. The criteria presented in this publication are such scientific assessments. Such water quality criteria associated with specific stream uses when adopted as State water quality standards under section 303 become enforceable maximum acceptable levels of a pollutant in ambient waters. The water quality criteria adopted in the State water quality standards could have the same numerical limits as the criteria developed under section 304. However, in many situations States may want to adjust water quality criteria developed under section 304 to reflect local environmental conditions and human exposure patterns before incorporation into water quality standards. It is not until their adoption as part of the State water quality standards that the criteria become regulatory.

Guidelines to assist the States in the modification of criteria presented in this document, in the development of water quality standards, and in other water-related programs of this Agency, are being developed by EPA.

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CRITERIA DOCUMENT

COPPER

CRITERIA

Aquatic Life

For total recoverable copper the criterion to protect freshwater aquatic life as derived using the Guidelines is 5.6 $\mu g/l$ as a 24-hour average and the concentration (in $\mu g/l$) should not exceed the numerical value given by $e^{(0.94[\ln(\mathrm{hardness})]-1.23)}$ at any time. For example, at hardnesses of 50, 100, and 200 mg/l as $CaCO_3$ the concentration of total recoverable copper should not exceed 12, 22, and 43 $\mu g/l$ at any time.

For total recoverable copper the criterion to protect saltwater aquatic life as derived using the Guidelines is 4.0 $\mu g/l$ as a 24-hour average and the concentration should not exceed 23 $\mu g/l$ at any time.

Human Health

Sufficient data are not available for copper to derive a level which would protect against the potential toxicity of this compound.

Using available organoleptic data, for controlling undesirable taste and odor quality of ambient water, the estimated level is 1 mg/l. It should be recognized that organoleptic data as a basis for establishing a water quality criteria have limitations and have no demonstrated relationship to potential adverse human health effects.

INTRODUCTION

Copper is a soft heavy metal, atomic number 29, with an atomic weight of 63.54, a melting point of 1,083°C, a boiling point of 2,595°C, and a density in elemental form at 20°C of 8.9 g/cc (Stecher, 1968). Elemental copper is readily attacked by organic and mineral acids that contain an oxidizing agent and is slowly soluble in dilute ammonia. The halogens attack copper slowly at room temperature to yield the corresponding copper halide. Oxides and sulfides are also reactive with copper.

Copper has two oxidation states: Cu I (cuprous) and Cu II (cupric). Cuprous copper is unstable in aerated water over the pH range of most natural waters (6 to 8) and will oxidize to the cupric state (Garrels and Christ, 1965). Bivalent copper chloride, nitrate, and sulfate are highly soluble in water, whereas basic copper carbonate, cupric hydroxide, oxide, and sulfide will precipitate out of solution or form colloidal suspensions in the presence of excess cupric ion. Cupric ions are also adsorbed by clays, sediments, and organic particulates and form complexes with several inorganic and organic compounds (Riemer and Toth, 1969; Stiff, 1971). Due to the complex interactions of copper with numerous other chemical species normally found in natural waters, the amounts of the various copper compounds and complexes that actually exist in solution will depend on the pH, temperature, alkalinity, and the concentrations of bicarbonate, sulfide, and organic ligands. Based on equilibrium constants, Stumm and Morgan (1970) calculated copper solubility in a carbonate-bearing water. They found that cupric ion (Cu^{2+}) would be the dominant copper species up to pH 6, and from pH 6 to 9.3 the aqueous copper carbonate complex ($CuCO_3$ aq) would dominate. The presence of organic ligands such as humic acids, fulvic acids, amino acids, cyanide, certain polypeptides, and detergents would alter this equilibrium (Stiff, 1971).

Zirino and Yamamoto (1972) developed a model to predict the distribution of copper species in seawater. Mixed ligand complexes and organic chelates were not considered in the model. They predicted that the distribution of copper species in seawater would vary significantly with pH and that $Cu(OH)_2$, $CuCO_3$, and Cu^{2+} would be the dominant species over the entire ambient pH range. The levels of $Cu(OH)_2$ increase from about 18 percent of the total copper at pH 7 to 90 percent at pH 8.6. $CuCO_3$ drops from about 30 percent at pH 7 to less than 0.1 percent at pH 8.6. Field and laboratory studies by Thomas and Grill (1977) indicate that copper adsorbed to sediments and particulates in freshwater may be released as soluble copper when it comes in contact with seawater in estuarine environments.

Copper is ubiquitous in the rocks and minerals of the earth's crust. In nature, copper occurs usually as sulfides and oxides and occasionally as metallic copper. Weathering and solution of these natural copper minerals results in background levels of copper in natural surface waters at concentrations generally well below 20 µg/l. Higher concentrations of copper are usually from anthropogenic sources. These sources include corrosion of brass and copper pipe by acidic waters, industrial effluents and fallout, sewage treatment plant effluents, and the use of copper compounds as aquatic algicides. Potential industrial copper pollution sources number in the tens of thousands in the United States. However, the major industrial sources include the smelting and refining industries, copper wire mills, coal burning industries, and iron and steel producing industries. Copper may enter natural waters either directly from these sources or by atmospheric fallout of air pollutants produced by these industries. Precipitation of atmospheric fallout may be a significant source of copper to the aquatic environment in industrial and mining areas.

The levels of copper able to remain in solution are directly dependent on water chemistry. Generally, ionic copper is more soluble in low pH, acidic waters and less soluble in high pH, alkaline waters.

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Aquatic Life Toxicology*

INTRODUCTION

Acute toxicity tests on copper have been conducted with 45 freshwater species and chronic tests with 15 species. Although the acute toxicity of copper seems to be related to water hardness, chronic toxicity apparently is not. Freshwater plants show a wide range of sensitivities to copper, but few data are available concerning bioconcentration by freshwater organisms.

Four fish and eighteen saltwater invertebrate species have been acutely exposed to copper. Results of these tests indicate a range of acute sensitivities from 28 µg/l for the summer flounder to 600 µg/l for the shore crab. Most of these tests were conducted using static procedures; however, seven species were exposed in flow-through tests with measurements of the concentrations of copper. Chronic data are available for only one species, but bioconcentration tests have been conducted with a wide variety of species.

Copper, which occurs in natural waters primarily as the divalent cupric ion in free and complex forms, is a minor nutrient for both plants and animals at low concentrations but is toxic to aquatic life at concentrations not too much higher. Concentrations of 1 to 10 µg/l are usually reported for unpolluted surface waters in the United States, but concentrations in the vicinity of municipal and industrial outfalls, particularly from smelting, refining, or metal plating industries, may be much higher.

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*The reader is referred to the Guidelines for Deriving Water Quality Criteria for the Protection of Aquatic Life and Its Uses in order to better understand the following discussion and recommendation. The following tables contain the appropriate data that were found in the literature, and at the bottom of each table are calculations for deriving various measures of toxicity as described in the Guidelines.

The cupric ion is highly reactive and forms moderate to strong complexes and precipitates with many inorganic and organic constituents of natural waters, e.g., carbonate, phosphate, amino acids and humates, and is readily absorbed on surfaces of suspended solids. The proportion of copper present as the free cupric ion is generally low and may be less than 1 percent in eutrophic waters where complexation predominates. Various copper complexes and precipitates appear to be largely nontoxic and tend to mask and remove toxicity attributable to copper (Andrew, 1976). This fact greatly complicates the interpretation and application of available toxicity data, because the proportion of free cupric ion present is highly variable and is difficult to measure except under special laboratory conditions. Few toxicity data have been reported using measurements other than total or dissolved copper.

Of the analytical measurements currently available, a water quality criterion for copper is probably best stated in terms of total recoverable copper, because of the variety of forms that can exist in natural waters and the various chemical and toxicological properties of these forms. The commonly occurring forms not measured by the total recoverable procedure, e.g., copper occluded in suspended mineral particulates, are forms that are less available to aquatic life and probably will not be converted to the more toxic forms readily under various natural conditions. The procedure for total recoverable copper, however, does measure those forms directly toxic to aquatic life, e.g., the free ion, and those labile forms (hydroxide, carbonate, and some phosphate precipitates) readily converted to more toxic forms under various natural conditions. Since the criteria are derived on the basis of tests conducted using soluble inorganic copper salts, total and total recoverable copper concentrations in the tests should be nearly equivalent, and the results are used interchangeably.

Because a majority of the reported test results (Tables 1 and 2) have been conducted with oligotrophic waters having relatively low complexing capacities, the criteria derived herein may be at or below ambient total copper concentrations in some surface waters of the United States. Seasonally and locally, toxicity in these waters may be mitigated by the presence of naturally occurring chelating, complexing, and precipitating agents. In addition, removal from the water column may be rapid due to normal growth of the more resistant aquatic organisms and settling of solids. The various forms of copper are in dynamic equilibrium and any change in chemical conditions, e.g., pH, could rapidly alter the proportion of the various forms present and, therefore, toxicity.

Since increasing calcium hardness and associated carbonate alkalinity are both known to reduce the acute toxicity of copper, expression of the upper limit as a function of water hardness allows adjustment for these water quality effects. This results in a much better fit with the available acute toxicity data, because the upper limit is higher at high hardness to reflect calcium antagonism and carbonate complexation. Some data on the relationship of toxicity to other factors, i.e., temperature, alkalinity, size of organism, and total organic carbon, are available for a limited number of species and will be discussed later.

The following data on the effects of copper on aquatic biota (Tables 1 through 6) have been summarized from the literature from 1950 to 1980. Efforts to obtain residue data, or effects data on algae and other plants, were not exhaustive, since previous reviews have indicated that these effects are of minor importance relative to toxicity of copper to fish and invertebrate species.

All concentrations are reported as copper, not as the compound.

EFFECTS

Acute Toxicity

Acute toxicity tests with copper have been conducted on 18 invertebrate and 27 fish species (Table 1), with approximately 175 acute values available for comparison. Most of these tests have been conducted with four salmonid species, fathead and bluntnose minnows, and bluegills. The acute values range from a low of 7.24 µg/l for Daphnia pulicaria in soft water to 10,200 µg/l for bluegills tested in hard water. The majority of tests conducted since about 1970 have been flow-through tests with measurements of both total and dissolved copper. For comparative purposes, only values expected to be equivalent to total recoverable copper were included in the tables.

Results of Cairns, et al. (1978) (Table 6) indicate that daphnids are more resistant to copper at low temperatures in acute tests. Since such data were not available for other species or for longer tests, no generalizations could be made for criteria derivation. Chakoumakos, et al. (1979) and Howarth and Sprague (1978) (Tables 1 and 6) have reported that larger (10 to 30 g) rainbow trout are approximately 2.5 to 3.0 times more resistant to copper than juveniles. This factor is obviously a source of variation in Table 1. However, insufficient data are available for other species to allow adjustment of test results or on which to base criteria recommendations. An additional complicating factor is the general lack of knowledge of the range of sensitivity of various life stages of most invertebrate species, or the effects on susceptibility, of starvation and other stress factors under natural conditions.

Lind, et al. (Manuscript) (Table 1) and Brown et al. (Table 6)(1974) have shown quantitative relationships between the acute toxicity of copper and naturally occurring organic chelating agents. Although these relationships have been demonstrated for only a few species (Daphnia magna, fathead minnow, and rainbow trout), the effects shown should be generalizable through chemical effects on cupric ion activity and bioavailability. Lind et al. (Manuscript) measured the toxicity of copper in a variety of surface waters and found that total organic carbon (T.O.C.) is a more important variable than hardness, with Daphnia magna acute values varying approximately 30-fold over the range of T.O.C. covered. Similar results were obtained with fathead minnows. This would indicate that the criteria should be adjusted upward for surface waters with T.O.C. significantly above the 2 to 3 mg/l usually found in the waters used for toxicity tests.

An exponential equation was used to describe the observed relationship of toxicity to hardness by performing a least squares regression of the natural logarithms of the acute values on the natural logarithms of hardness. Sufficient data were available for Daphnia magna, Daphnia pulicaria, chinook salmon, cutthroat and rainbow trout, fathead minnows, and bluegills to show a correlation of acute toxicity and hardness. The slope of the regression equations ranged from 0.67 for chinook salmon to 1.34 for Daphnia magna with an arithmetic mean of 0.94. The close agreement of the slopes and the highly significant ($p = 0.01$) regressions in each case reflect the quality of the toxicological data available and confirm the premise that the effect of hardness on the acute toxicity of copper is similar for various aquatic animals.

In the absence of the contradictory data, it is assumed that the hardness relationship holds for the acute toxicity of copper to all freshwater aquatic animals. The mean slope (0.94) was fitted through the geometric mean toxicity value and hardness for each species to obtain a logarithmic intercept for each species. The species mean intercept, calculated as the exponential of the logarithmic intercept, was used as a measure of relative species sensitivity to copper (Table 3).

Daphnia pulicaria was found to be the most sensitive species. Two other daphnid species and the scud *Gammarus pseudolimnaeus* were only slightly less sensitive. Salmonids and the bluntnose minnows were nearly as sensitive as the daphnids, but fathead minnows and several other cyprinids were approximately 3 to 11 times more resistant. Bluegills and other centrarchids are approximately 10 to 100 times more resistant than salmonids.

A freshwater Final Acute Intercept of 0.29 μg/l was obtained for copper using the species mean acute intercepts listed in Table 3 and the calculation procedures described in the Guidelines. Thus the Final Acute Equation is $e^{(0.94[\ln(\text{hardness})]-1.23)}$.

The saltwater invertebrate data (Table 1) include investigations on three phyla: annelids, molluscs, and arthropods (crustaceans). The acute sensitivities of crustaceans ranged from 31 μg/l for *Acartia tonsa* (Sosnowski and Gentile, 1978) to 600 μg/l for shore crab, *Carcinus maenus* (Connors, 1972). Adult polychaete worm acute values ranged from 77 μg/l (Pesch and Morgan, 1978) to 480 μg/l (Jones, et al. 1976). Pesch and Morgan (1978) determined that the 96-hour LC_{50} for *Neanthes arenaceodentata* increased from 77 μg/l in a flowing water system to 200 μg/l in the presence of a sandy sediment. Jones, et al. (1976) indicated that *Nereis diversicolor* exhibited a variable response to salinity over a range of 5 to 34 g/kg with the greatest toxicity occurring at 5 g/kg. The lowest reported acute value for the bivalve molluscs was 39 μg/l for the soft-shelled clam, *Mya arenaria*

(Eisler, 1977), and the highest was 560 µg/l for the adult Pacific oyster, Crassostrea gigas (Okazaki, 1976). Eisler (1977) indicated that the sensitivity of Mya arenaria to copper varied according to the seasonal temperature, with copper being at least 100 times more toxic at 22°C than at 4°C. The arthropods (crustaceans) were both the most sensitive invertebrate species tested, with an acute value of 31 µg/l for Acartia tonsa (Sosnowski and Gentile, 1978), and the least sensitive of all animals tested, with an acute value of 600 µg/l for larvae of the shore crab, Carcinus maenus (Connor, 1972). Sosnowski, et al. (1979) showed that the sensitivity of field populations of Acartia tonsa to copper was strongly correlated with population density and food ration (Table 6), whereas cultured A. tonsa manifested a reproducible toxicological response to copper (Table 1) through six generations (Sosnowski and Gentile, 1978). Johnson and Gentile (1979) reported that lobster larvae appear to be twice as sensitive to copper as the adults.

The acute values for saltwater fishes include data for four species and two different life history stages (Table 1). Acute toxicity ranged from 28 µg/l for summer flounder embryos, Paralichthys dentatus (U.S. EPA, 1980) to 510 µg/l for the Florida pompano, Trachinotus carolinus (Birdsong and Avavit, 1971). The results of the acute tests on the embryos of summer and winter flounder were used in Table 1 because embryos of these species apparently are not resistant to copper and because other acute values are not available for these species.

Studies on the effect of salinity on the toxicity of copper indicate that it is more toxic to adult pompano at 10 g/kg than at 30 g/kg (Birdsong and Avavit 1971). Other species of saltwater fish were tested for sensitivity to copper, but the experimental conditions were not suitable for inclusion in either the acute or chronic tables; consequently, these data were placed in Table 6. Also, a number of scientists exposed anadromous species such as Atlantic and coho salmon to copper in freshwater. These data were utilized in deriving the freshwater criterion, but not the saltwater criterion.

A Saltwater Final Acute Value of 22.9 μg/l was obtained for copper using the species mean acute values in Table 3 and the calculation procedures described in the Guidelines.

Chronic Toxicity

The data base for chronic toxicity of copper to freshwater aquatic animals (Table 2) includes chronic values for four invertebrate and eleven fish species. Life cycle test results are available for two snails, *Daphnia magna* at three hardnesses, an amphipod, brook trout, bluntnose minnow, fathead minnow at four hardnesses, and the bluegill. Early life stage tests have been conducted with several additional fish species, including channel catfish at two hardnesses. The chronic values range from a low of 3.9 μg/l for early life stage tests with brook trout in soft water to 60.4 μg/l for a similar test with northern pike. Values for invertebrate species nearly overlap those for fish with a range of 6.1 to 29.0 μg/l. A series of tests with *Daphnia magna* in a hard pond water (Table 6) with unmeasured copper concentrations resulted in chronic values of about 49 μg/l.

The data available concerning the effect of hardness on the chronic toxicity of copper is somewhat nebulous. The total range of chronic values is 3.9 to 60.4 μg/l (Table 2), which is much less than the range of 0.23 to 260 μg/l for species mean acute intercepts (Table 3). This may be due to differences in the kinds and numbers of species and waters used in the two kinds of tests, but it may also indicate that hardness affects chronic toxicity of copper differently than it affects acute toxicity. Indeed, in chronic tests with Daphnia magna, Chapman, et al. (Manuscript) found that copper was less toxic at a medium hardness than at a low hardness but was most toxic at a high hardness (Table 2). They indicated that in the high hardness tests the daphnids probably ingested some precipitated copper. Also, some copper probably sorbed onto suspended food particles. These factors were not expected to impact chronic toxicity to species which are not filter feeders, however.

Sauter, et al. (1976) found that hardness affected the chronic toxicity of copper to channel catfish very little, if at all, and the four results available for brook trout do not show any consistent relationship. The four chronic tests with the fathead minnow also showed a consistent but small effect of hardness on chronic toxicity. The slope of 0.26 is not statistically significant and is much less than the acute mean slope of 0.94. A chronic value (Table 6) from a test conducted with the fathead minnow in a hard stream water contaminated with sewage effluent (Brungs, et al. 1976) was more than twice other values for this species. This probably indicates that the high levels of hardness, phosphate, and organic material reduced the chronic toxicity of copper in this stream. On the other hand, a factor of two reduction in toxicity is rather small considering the much greater reductions that occur in acute toxicity of copper.

Acute-chronic ratios for copper (Table 3) vary widely, even for tests with the same species. The highest ratios (38 and 156) are for two of the more acutely resistant species, bluegills and Campeloma decisum (a snail). Ratios for three tests with D. magna ranged from 1.2 to 7.3, and for four tests with fathead minnows from 5.4 to 20. The more sensitive species have ratios below 4, whereas the less sensitive species have ratios above 4. Also, the ratio seems to increase with hardness.

The available evidence seems to indicate that hardness affects the acute-chronic ratio but not the chronic toxicity of copper. Chronic tests have been conducted with quite a variety of aquatic animals and present a good indication of the range of chronic sensitivity to copper. The Freshwater Final Chronic Value for copper, derived from the species mean chronic values listed in Table 2 using the calculation procedures described in the Guidelines, is 5.6 µg/l.

The only chronic value reported (Table 2) for a saltwater species was that for the mysid shrimp, Mysidopsis bahia (U.S. EPA, 1980). The chronic toxicity of copper to this saltwater invertebrate was determined in a flow-through life cycle exposure in which the concentrations of copper were measured by atomic absorption spectroscopy. Groups of 20 individuals were reared in each of five copper concentrations (control = 2.9 ± 0.5 µg/l, 24.2 ± 7.0 µg/l, 38.5 ± 6.3 µg/l, 77.4 ± 7.4 µg/l, 140.2 ± 11.8 µg/l) for 46 days at 20°C and 30 g/kg salinity. The biological responses examined included time of appearance of first brood, the number of spawns, mean brood size, and growth. The appearance of embryos in the brood sac was delayed for 6 and 8 days at 77 µg/l and 140 µg/l, respectively. The number of spawns recorded at 77 µg/l was significantly ($p < 0.05$) fewer than at 38.5 µg/l. The number of spawns at 24 and 38 µg/l was not significantly different from the control. Brood size was significantly ($p < 0.05$) reduced at 77 µg/l but not at lower concentrations, and no effects on growth were detected at any of the copper concentrations. Based upon reproductive data, adverse effects were observed at 38 µg/l, but not at 77 µg/l, resulting in a chronic value of 54 µg/l. Using the acute value of 181 µg/l, the acute-chronic ratio for this species is 3.4.

The species mean acute-chronic ratios of 38 and 156 appear to be high (Table 3), but the other seven are all within a factor af 10. The geometric mean of these seven is 5.78. If the Saltwater Final Acute Value of 22.9 µg/l is divided by the acute-chronic ratio of 5.78, a Saltwater Final Chronic Value of 4.0 µg/l is obtained.

Plant Effects

Copper has been widely used as an algicide and herbicide for nuisance aquatic plants. Although it is known as an inhibitor of photosynthesis and plant growth, toxicity data on individual species (Table 4) are not numerous. The relationship of toxicity to water chemistry and the importance of the culture medium on toxicity has only recently been recognized (Gachter, et al. 1973).

Copper concentrations from 1 to 8,000 µg/l have been shown to inhibit growth of various plant species. Several of the values are near or below the chronic values for fish and invertebrate species, but most are much higher. No Final Plant Value can be obtained because none of the plant values were based on measured concentrations.

For saltwater algae the concentrations of copper which cause a 50 percent reduction in photosynthesis or growth are tabulated in Table 4 for one species of macro-algae and eight species of micro-algae. The most sensitive species were *Thalassiosira pseudonana* and *Scrippsiella faeroense* which were inhibited by 5 µg/l.

Residues

Bioconcentration factors (Table 5) ranged from zero for the bluegill to 2,000 for the alga *Chlorella regularis*. Because copper is a required element for animal nutrition, the significance of copper residues has never been established, and few tests have been run for the purpose of determining bioconcentration factors.

Copper is an essential element in the respiratory pigments of some saltwater invertebrates, especially crustaceans, and plants have enzymes which contain copper and are necessary for photosynthesis. However, copper is also bioconcentrated in excess of any known needs by several saltwater species (Table 5). The polychaete worm, Neanthes arenaceodentata, bioconcentrated copper 2,550 times (Pesch and Morgan, 1978), whereas in a series of measurements with algae by Riley and Roth (1971) the highest reported concentration factor was 617 for Heteromastix Longifillis.

The highest bioconcentration factors for copper are those for the bivalve molluscs. Shuster and Pringle (1969) found that the American oyster could concentrate copper 28,200 times after a 140-day continuous exposure to 50 µg/l. Even though the tissue of the oyster became bluish-green in color, mortalities at this level were only slightly higher than the controls. This amount of copper is not known to be harmful to man, but there have been instances recorded that oysters have been unmarketable because of their green appearance due to high copper content.

Because no maximum permissible tissue concentration exists, neither a freshwater nor a saltwater Final Residue Value can be calculated.

Miscellaneous

The results of many additional tests of the effects of copper on freshwater aquatic organisms are listed in Table 6. Many of these are acute tests with non-standard durations for the organisms used. Many of the other acute tests in Table 6 were conducted in dilution waters which were known to contain materials which would significantly reduce the toxicity of copper. These reductions were different from those caused by hardness, and not enough data exist to account for these in the derivation of the criteria. For example, Lind, et al. (Manuscript) conducted tests with Daphnia pulicaria and fathead minnow in waters with concentrations of T.O.C. ranging up to 34 mg/l. Similarly, Geckler, et al. (1976) and Brungs, et al. (1976) conducted tests with many species in stream water which contained a large amount of effluent from a sewage treatment plant. Also, Wallen, et al. (1957) tested mosquitofish in a turbid pond water. Until chemical measurements which correlate well with the toxicity of copper in a wide variety of waters are identified and widely used, results of tests in unusual dilution waters, such as those in Table 6, will not be very useful for deriving water quality criteria.

Longer exposures than the standard acute studies have been recorded in Table 6. Most noteworthy are the values reported for the bay scallop Argopecten irradiens (U.S. EPA, 1980), which suffered mortality and reduced growth at concentrations of 5 and 5.8 μg/l, respectively. Even though several studies have been reported on the sublethal effects on survival, growth, and reproduction, the significance of these effects has yet to be evaluated. However, these studies do indicate existence of demonstrable lethal effects due to chronic exposure at very low concentrations of copper.

Summary

Acute toxicity data are available for 45 species of freshwater animals. The approximately 175 acute values range from 7.2 μg/l for Daphnia pulicaria in soft water to 10,200 μg/l for the bluegill in hard water. Statistically significant regressions of acute toxicity on water hardness are available for seven species, with toxicity decreasing as hardness increases. Additional data for several species indicate that toxicity also decreases with increases in alkalinity and total organic carbon.

The range of acute values indicates that some of the more resistant species could survive in copper concentrations over 100 times that which would be readily lethal to the more sensitive species. Among the more sensitive species are daphnids, scuds, midges, and snails which form the major food-webs for both warm- and cold-water fishes. Concentrations of copper lethal to these sensitive organisms in soft water are only slightly above those chronically toxic to most fish and invertebrate species.

Chronic values are available for 15 freshwater species, ranging from a low of 3.9 µg/l for brook trout to 60.4 µg/l for northern pike. Hardness does not appear to affect the chronic toxicity of copper. Fish and invertebrate species seem to be about equally sensitive to the chronic toxicity of copper. The two most sensitive species, bluntnose minnow and G. pseudolimnea, are both important food organisms.

Copper toxicity has been tested on a wide range of plant species, with results approximating those for animals. Complexing effects of the test media and a lack of good analytical data make interpretation and application of these results difficult. Protection of animal species, however, appears to offer adequate protection of plants as well. Copper does not appear to bioconcentrate very much in the edible portion of freshwater aquatic species.

The acute toxicity of copper to saltwater animals ranges from 17 µg/l for a calonoid cupepod to 600 µg/l for the shore crab. A chronic lifecycle test has been conducted with the mysid shrimp, and adverse effects were observed at 77 µg/l but not at 38 µg/l which resulted in an acute-chronic ratio of 3.4. Several saltwater algal species have been tested, and effects were observed between 5 and 100 µg/l. Oysters can bioaccumulate copper up to 28,200 times, and become bluish-green, apparently without significant mortality. In long-term exposures, the bay scallop was killed at 5 µg/l.

CRITERIA

For total recoverable copper the criterion to protect freshwater aquatic life as derived using the Guidelines is 5.6 µg/l as a 24-hour average, and the concentration (in μg/l) should not exceed the numerical value given by $e^{(0.94[\ln(\text{hardness})]-1.23)}$ at any time. For example, at hardnesses of 50, 100, and 200 mg/l as $CaCO_3$ the concentration of total recoverable copper should not exceed 12, 22, and 43 μg/l at any time.

For total recoverable copper the criterion to protect saltwater aquatic life as derived using the Guidelines is 4.0 μg/l as a 24-hour average, and the concentration should not exceed 23 μg/l at any time.

Table 1. Acute values for copper

Species	Method*	Chemical	Hardness (mg/l as $CaCO_3$)	LC50/EC50 (µg/l)**	Species Mean Acute Value (µg/l)**	Reference
			FRESHWATER SPECIES			
Worm, *Limnodrilus hoffmeisteri*	S, U	Copper sulfate	100	102	-	Wurtz & Bridges, 1961
Worm, *Nais* sp.	S, M	-	50	90	-	Rehwoldt, et al. 1973
Snail (adult), *Amnicola* sp.	S, M	-	50	900	-	Rehwoldt, et al. 1973
Snail, *Campeloma decisum*	FT, M	Copper sulfate	35-55	1,700	-	Arthur & Leonard, 1970
Snail, *Gyraulus circumstriatus*	S, U	Copper sulfate	100	108	-	Wurtz & Bridges, 1961
Snail, *Physa heterostropha*	S, U	Copper sulfate	100	69	-	Wurtz & Bridges, 1961
Snail, *Physa integra*	FT, M	Copper sulfate	35-55	39	-	Arthur & Leonard, 1970
Cladoceran, *Daphia magna*	S, U	Copper sulfate	226	200	-	Cabejszek & Stasiak, 1960
Cladoceran, *Daphnia magna*	R, U	Copper chloride	45.3	9.8	-	Biesinger & Christensen, 1972
Cladoceran, *Daphnia magna*	S, U	Copper chloride	99	65	-	Adema & Degroot-Van Zijl, 1972
Cladoceran, *Daphnia magna*	S, U	Copper chloride	99	30	-	Adema & Degroot-Van Zijl, 1972
Cladoceran, *Daphnia magna*	S, U	Copper sulfate	120	12.7	-	Anderson, 1948
Cladoceran, *Daphnia magna*	S, U	Copper sulfate	-	100	-	Bringmann & Kuhn, 1959
Cladoceran, *Daphnia magna*	S, M	Copper chloride	52	26	-	Chapman, et al. Manuscript

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/l as $CaCO_3$)	LC50/EC50 (µg/l)**	Species Mean Acute Value (µg/l)**	Reference
Cladoceran, *Daphnia magna*	S, M	Copper chloride	105	30	-	Chapman, et al. Manuscript
Cladoceran, *Daphnia magna*	S, M	Copper chloride	106	38	-	Chapman, et al. Manuscript
Cladoceran, *Daphnia magna*	S, M	Copper chloride	207	69	-	Chapman, et al. Manuscript
Cladoceran, *Daphnia magna*	S, U	Copper sulfate	45	10	-	Cairns, et al. 1978
Cladoceran, *Daphnia pulex*	S, U	Copper sulfate	45	10	-	Cairns, et al. 1978
Cladoceran, *Daphnia pulicaria*	R, M	-	48	11.4	-	Lind, et al. Manuscript
Cladoceran, *Daphnia pulicaria*	R, M	-	48	9.06	-	Lind, et al. Manuscript
Cladoceran, *Daphnia pulicaria*	R, M	-	48	7.24	-	Lind, et al. Manuscript
Cladoceran, *Daphnia pulicaria*	R, M	-	44	10.8	-	Lind, et al. Manuscript
Cladoceran, *Daphnia pulicaria*	R, M	-	45	9.3	-	Lind, et al. Manuscript
Cladoceran, *Daphnia pulicaria*	R, M	-	95	17.8	-	Lind, et al. Manuscript
Cladoceran, *Daphnia pulicaria*	R, M	-	145	23.7	-	Lind, et al. Manuscript
Cladoceran, *Daphnia pulicaria*	R, M	-	245	27.3	-	Lind, et al. Manuscript
Scud, *Gammarus pseudolimnaeus*	FT, M	Copper sulfate	35-55	20	-	Arthur & Leonard, 1970

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/l as $CaCO_3$)	LC50/EC50 (µg/l)**	Species Mean Acute Value (µg/l)**	Reference
Scud, *Gammarus* sp.	S, M	-	50	910	-	Rehwoldt, et al. 1973
Crayfish, *Orconectes rusticus*	FT, M	Copper sulfate	100-125	3,000	-	Hubschman, 1967
Stonefly, *Acroneuria lycorias*	S, M	Copper sulfate	40	8,300	-	Warnick & Bell, 1969
Damselfly, Unidentified	S, M	-	50	4,600	-	Rehwoldt, et al. 1973
Midge, *Chironomus* sp.	S, M	-	50	30	-	Rehwoldt, et al. 1973
Caddisfly, Unidentified	S, M	-	50	6,200	-	Rehwoldt, et al. 1973
Rotifer, *Philodina acuticornis*	S, M	Copper sulfate	40	160	-	Buikema, et al. 1977
Rotifer, *Philodina acuticornis*	R, U	Copper sulfate	25	700	-	Buikema, et al. 1974
Rotifer, *Philodina acuticornis*	R, U	Copper sulfate	81	1,100	-	Buikema, et al. 1974
American eel, *Anguilla rostrata*	S, M	Copper nitrate	53	6,400	-	Rehwoldt, et al. 1971
American eel, *Anguilla rostrata*	S, M	-	55	6,000	-	Rehwoldt, et al. 1972
Coho salmon (adult), *Oncorhynchus kisutch*	FT, M	Copper chloride	20	46	-	Chapman & Stevens, 1978
Coho salmon (yearling), *Oncorhynchus kisutch*	S, M	Copper chloride	89-99	74	-	Lorz & McPherson, 1976
Coho salmon (yearling), *Oncorhynchus kisutch*	S, M	Copper chloride	89-99	70	-	Lorz & McPherson, 1976

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/l as $CaCO_3$)	LC50/EC50 (µg/l)**	Species Mean Acute Value (µg/l)**	Reference
Coho salmon (smolt), *Oncorhynchus kisutch*	S, M	Copper chloride	89-99	60	-	Lorz & McPherson, 1976
Chinook salmon (alevin), *Oncorhynchus tshawytscha*	FT, M	-	25	26	-	Chapman, 1978
Chinook salmon (swim-up), *Oncorhynchus tshawytscha*	FT, M	-	25	19	-	Chapman, 1978
Chinook salmon (parr), *Oncorhnychus tshawytscha*	FT, M	-	25	38	-	Chapman, 1978
Chinook salmon (smolt), *Oncorhynchus tshawytscha*	FT, M	-	25	26	-	Chapman, 1978
Chinook salmon, *Oncorhynchus tshawytscha*	FT, M	-	13	10	-	Chapman & McCrady, 1977
Chinook salmon, *Oncorhynchus tshawytscha*	FT, M	-	46	22	-	Chapman & McCrady, 1977
Chinook salmon, *Oncorhynchus tshawytscha*	FT, M	-	182	85	-	Chapman & McCrady, 1977
Chinook salmon, *Oncorhynchus tshawytscha*	FT, M	-	359	130	-	Chapman & McCrady, 1977
Cutthroat trout, *Salmo clarki*	FT, M	Copper chloride	205	367	-	Chakoumakos, et al. 1979
Cutthroat trout, *Salmo clarki*	FT, M	Copper chloride	70	186	-	Chakoumakos, et al. 1979
Cutthroat trout, *Salmo clarki*	FT, M	Copper chloride	18	36.8	-	Chakoumakos, et al. 1979
Cutthroat trout, *Salmo clarki*	FT, M	Copper chloride	204	232	-	Chakoumakos, et al. 1979
Cutthroat trout, *Salmo clarki*	FT, M	Copper chloride	83	162	-	Chakoumakos, et al. 1979

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/l as $CaCO_3$)	LC50/EC50 (µg/l)**	Species Mean Acute Value (µg/l)**	Reference
Cutthroat trout, Salmo clarki	FT, M	Copper chloride	31	73.6	-	Chakoumakos, et al. 1979
Cutthroat trout, Salmo clarki	FT, M	Copper chloride	160	91	-	Chakoumakos, et al. 1979
Cutthroat trout, Salmo clarki	FT, M	Copper chloride	74	44.4	-	Chakoumakos, et al. 1979
Cutthroat trout, Salmo clarki	FT, M	Copper chloride	26	15.7	-	Chakoumakos, et al. 1979
Rainbow trout, Salmo gairdneri	FT, M	Copper sulfate	30	19.9	-	Howarth & Sprague, 1978
Rainbow trout, Salmo gairdneri	FT, M	Copper sulfate	32	22.4	-	Howarth & Sprague, 1978
Rainbow trout, Salmo gairdneri	FT, M	Copper sulfate	31	28.9	-	Howarth & Sprague, 1978
Rainbow trout, Salmo gairdneri	FT, M	Copper sulfate	31	30	-	Howarth & Sprague, 1978
Rainbow trout, Salmo gairdneri	FT, M	Copper sulfate	30	30	-	Howarth & Sprague, 1978
Rainbow trout, Salmo gairdneri	FT, M	Copper sulfate	101	176	-	Howarth & Sprague, 1978
Rainbow trout, Salmo gairdneri	FT, M	Copper sulfate	101	40	-	Howarth & Sprague, 1978
Rainbow trout, Salmo gairdneri	FT, M	Copper sulfate	99	33.1	-	Howarth & Sprague, 1978
Rainbow trout, Salmo gairdneri	FT, M	Copper sulfate	102	30.7	-	Howarth & Sprague, 1978
Rainbow trout, Salmo gairdneri	FT, M	Copper sulfate	101	46.3	-	Howarth & Sprague, 1978

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/l as $CaCO_3$)	LC50/EC50 (µg/l)**	Species Mean Acute Value (µg/l)**	Reference
Rainbow trout, *Salmo gairdneri*	FT, M	Copper sulfate	99	47.9	-	Howarth & Sprague, 1978
Rainbow trout, *Salmo gairdneri*	FT, M	Copper sulfate	100	48.1	-	Howarth & Sprague, 1978
Rainbow trout, *Salmo gairdneri*	FT, M	Copper sulfate	100	81.1	-	Howarth & Sprague, 1978
Rainbow trout, *Salmo gairdneri*	FT, M	Copper sulfate	98	85.9	-	Howarth & Sprague, 1978
Rainbow trout, *Salmo gairdneri*	FT, M	Copper sulfate	370	232	-	Howarth & Sprague, 1978
Rainbow trout, *Salmo gairdneri*	FT, M	Copper sulfate	366	70	-	Howarth & Sprague, 1978
Rainbow trout, *Salmo gairdneri*	FT, M	Copper sulfate	371	82.2	-	Howarth & Sprague, 1978
Rainbow trout, *Salmo gairdneri*	FT, M	Copper sulfate	361	298	-	Howarth & Sprague, 1978
Rainbow trout, *Salmo gairdneri*	FT, M	Copper chloride	194	169	-	Chakoumakos, et al. 1979
Rainbow trout, *Salmo gairdneri*	FT, M	Copper chloride	194	85.3	-	Chakoumakos, et al. 1979
Rainbow trout, *Salmo gairdneri*	FT, M	Copper chloride	194	83.3	-	Chakoumakos, et al. 1979
Rainbow trout, *Salmo gairdneri*	FT, M	Copper chloride	194	103	-	Chakoumakos, et al. 1979
Rainbow trout, *Salmo gairdneri*	FT, M	Copper chloride	194	274	-	Chakoumakos, et al. 1979
Rainbow trout, *Salmo gairdneri*	FT, M	Copper chloride	194	128	-	Chakoumakos, et al. 1979

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/l as $CaCO_3$)	LC50/EC50 (µg/l)**	Species Mean Acute Value (µg/l)**	Reference
Rainbow trout, *Salmo gairdneri*	FT, M	Copper chloride	194	221	-	Chakoumakos, et al. 1979
Rainbow trout, *Salmo gairdneri*	FT, M	Copper chloride	194	165	-	Chakoumakos, et al. 1979
Rainbow trout, *Salmo gairdneri*	FT, M	Copper chloride	194	197	-	Chakoumakos, et al. 1979
Rainbow trout, *Salmo gairdneri*	FT, M	Copper chloride	194	514	-	Chakoumakos, et al. 1979
Rainbow trout, *Salmo gairdneri*	FT, M	Copper chloride	194	243	-	Chakoumakos, et al. 1979
Rainbow trout (alevin), *Salmo gairdneri*	FT, M	-	25	28	-	Chapman, 1978
Rainbow trout (swim-up), *Salmo gairdneri*	FT, M	-	25	17	-	Chapman, 1978
Rainbow trout (parr), *Salmo gairdneri*	FT, M	-	25	18	-	Chapman, 1978
Rainbow trout (smolt), *Salmo gairdneri*	FT, M	-	25	29	-	Chapman, 1978
Rainbow trout (adult), *Salmo gairdneri*	FT, M	Copper chloride	42	57	-	Chapman & Stevens, 1978
Rainbow trout, *Salmo gairdneri*	FT, M	Copper sulfate	350	102	-	Fogels & Sprague, 1977
Rainbow trout, *Salmo gairdneri*	FT, M	Copper sulfate	125	200	-	Spear, 1977
Rainbow trout, *Salmo gairdneri*	FT, M	Copper sulfate	125	190	-	Spear, 1977
Rainbow trout, *Salmo gairdneri*	FT, M	Copper sulfate	125	210	-	Spear, 1977

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/l as $CaCO_3$)	LC50/EC50 (µg/l)**	Species Mean Acute Value (µg/l)**	Reference
Rainbow trout, *Salmo gairdneri*	S, M	Copper sulfate	290	890	-	Calamari & Marchetti, 1973
Atlantic salmon, *Salmo salar*	FT, M	Copper sulfate	20	48	-	Sprague, 1964
Atlantic salmon, *Salmo salar*	S, M	-	8-10	125	-	Wilson, 1972
Atlantic salmon, *Salmo salar*	FT, M	-	14	32	-	Sprague & Ramsay, 1965
Brook trout, *Salvelinus fontinalis*	FT, M	Copper sulfate	45	100	-	McKim & Benoit, 1971
Stoneroller, *Campostoma anomalum*	FT, M	Copper sulfate	200	290	-	Geckler, et al. 1976
Goldfish, *Carassius auratus*	S, U	Copper sulfate	20	36	-	Pickering & Henderson, 1966
Goldfish, *Carassius auratus*	FT, M	Copper sulfate	52	300	-	Tsai & McKee, 1980
Carp, *Cyprinus carpio*	S, M	Copper nitrate	53	810	-	Rehwoldt, et al. 1971
Carp, *Cyprinus carpio*	S, M	-	55	800	-	Rehwoldt, et al. 1972
Longfin dace, *Agosia chrysogaster*	R, M	Copper sulfate	221	860	-	Lewis, 1978
Striped shiner, *Notropis chrysocephalus*	FT, M	Copper sulfate	200	790	-	Geckler, et al. 1976
Striped shiner, *Notropis chrysocephalus*	FT, M	Copper sulfate	200	1,900	-	Geckler, et al. 1976
Bluntnose minnow, *Pimephales notatus*	FT, M	Copper sulfate	200	290	-	Geckler, et al. 1976

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/l as $CaCO_3$)	LC50/EC50 (µg/l)**	Species Mean Acute Value (µg/l)**	Reference
Bluntnose minnow, *Pimephales notatus*	FT, M	Copper sulfate	200	260	-	Geckler, et al. 1976
Bluntnose minnow, *Pimephales notatus*	FT, M	Copper sulfate	200	260	-	Geckler, et al. 1976
Bluntnose minnow, *Pimephales notatus*	FT, M	Copper sulfate	200	280	-	Geckler, et al. 1976
Bluntnose minnow, *Pimephales notatus*	FT, M	Copper sulfate	200	340	-	Geckler, et al. 1976
Bluntnose minnow, *Pimephales notatus*	FT, M	Copper sulfate	194	210	-	Horning & Neiheisel, 1979
Bluntnose minnow, *Pimephales notatus*	FT, M	Copper sulfate	194	220	-	Horning & Neiheisel, 1979
Bluntnose minnow, *Pimephales notatus*	FT, M	Copper sulfate	194	270	-	Horning & Neiheisel, 1979
Fathead minnow, *Pimephales promelas*	FT, M	Copper sulfate	202	460	-	Pickering, et al. 1977
Fathead minnow, *Pimephales promelas*	FT, M	Copper sulfate	202	490	-	Pickering, et al. 1977
Fathead minnow, *Pimephales promelas*	FT, M	-	200	790	-	Andrew, 1976
Fathead minnow, *Pimephales promelas*	FT, M	-	45	200	-	Andrew, 1976
Fathead minnow, *Pimephales promelas*	S, U	Copper sulfate	360	1,450 (2)***	-	Pickering & Henderson, 1966
Fathead minnow, *Pimephales promelas*	S, U	Copper sulfate	20	23 (4)***	-	Pickering & Henderson, 1966
Fathead minnow, *Pimephales promelas*	S, U	Copper sulfate	200	430	-	Mount, 1968

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/l as $CaCO_3$)	LC50/EC50 (µg/l)**	Species Mean Acute Value (µg/l)**	Reference
Fathead minnow, *Pimephales promelas*	FT, M	Copper sulfate	200	470	-	Mount & Stephan, 1969
Fathead minnow, *Pimephales promelas*	S, U	Copper sulfate	31	84	-	Mount & Stephan, 1969
Fathead minnow, *Pimephales promelas*	FT, M	Copper sulfate	31	75	-	Mount & Stephan, 1969
Fathead minnow, *Pimephales promelas*	FT, M	Copper sulfate	200	440	-	Geckler, et al. 1976
Fathead minnow, *Pimephales promelas*	FT, M	Copper sulfate	200	490	-	Geckler, et al. 1976
Fathead minnow, *Pimephales promelas*	FT, M	-	48	114	-	Lind, et al. Manuscript
Fathead minnow, *Pimephales promelas*	FT, M	-	45	121	-	Lind, et al. Manuscript
Fathead minnow, *Pimephales promelas*	FT, M	-	46	88.5	-	Lind, et al. Manuscript
Blacknose dace, *Rhinichthys atratulus*	FT, M	Copper sulfate	200	320	-	Geckler, et al. 1976
Creek chub, *Semotilus atromaculatus*	FT, M	Copper sulfate	200	310	-	Geckler, et al. 1976
Brown bullhead, *Ictalurus nebulosus*	FT, M	Copper sulfate	202	180 (2)***	-	Brungs, et al. 1973
Brown bullhead, *Ictalurus nebulosus*	FT, M	Copper sulfate	200	540	-	Geckler, et al. 1976
Banded killifish, *Fundulus diaphanus*	S, M	Copper nitrate	53	860	-	Rehwoldt, et al. 1971
Banded killifish, *Fundulus diaphanus*	S, M	-	55	840	-	Rehwoldt, et al. 1972

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/l as $CaCO_3$)	LC50/EC50 (µg/l)**	Species Mean Acute Value (µg/l)**	Reference
Flagfish, *Jordanella floridae*	FT, M	-	350-375	1,270	-	Fogels & Sprague, 1977
Guppy, *Poecilia reticulata*	S, U	Copper sulfate	20	36	-	Pickering & Henderson, 1966
Guppy, *Poecilia reticulata*	FT, M	-	87.5	112	-	Chynoweth, et al. 1976
Guppy, *Poecilia reticulata*	FT, M	-	67.2	138	-	Chynoweth, et al. 1976
White perch, *Morone americanus*	S, M	Copper nitrate	53	6,200	-	Rehwoldt, et al. 1971
White perch, *Morone americanus*	S, M	-	55	6,400	-	Rehwoldt, et al. 1972
Striped bass, *Morone saxatilis*	S, M	Copper nitrate	53	4,300	-	Rehwoldt, et al. 1971
Striped bass, *Morone saxatilis*	S, M	-	55	4,000	-	Rehwoldt, et al. 1972
Striped bass, *Morone saxatilis*	S, U	Copper sulfate	35	620	-	Wellborn, 1969
Striped bass (larva), *Morone saxatilis*	S, U	-	68.4	50	-	Hughes, 1973
Striped bass (larva), *Morone saxatilis*	S, U	-	68.4	100	-	Hughes, 1971
Striped bass (fingerling), *Morone saxatilis*	S, U	-	68.4	150	-	Hughes, 1971
Rainbow darter, *Etheostoma caeruleum*	FT, M	Copper sulfate	200	320	-	Geckler, et al. 1976
Orangethroat darter, *Etheostoma spectabile*	FT, M	Copper sulfate	200	850	-	Geckler, et al. 1976

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/l as $CaCO_3$)	LC50/EC50 (µg/l)**	Species Mean Acute Value (µg/l)**	Reference
Pumpkinseed, *Lepomis gibbosus*	S, M	Copper nitrate	53	2,400	-	Rehwoldt, et al. 1971
Pumpkinseed, *Lepomis gibbosus*	S, M	-	55	2,700	-	Rehwoldt, et al. 1972
Pumpkinseed, *Lepomis gibbosus*	FT, M	Copper sulfate	125	1,240	-	Spear, 1977
Pumpkinseed, *Lepomis gibbosus*	FT, M	Copper sulfate	125	1,300	-	Spear, 1977
Pumpkinseed, *Lepomis gibbosus*	FT, M	Copper sulfate	125	1,670	-	Spear, 1977
Pumpkinseed, *Lepomis gibbosus*	FT, M	Copper sulfate	125	1,940	-	Spear, 1977
Pumpkinseed, *Lepomis gibbosus*	FT, M	Copper sulfate	125	1,240	-	Spear, 1977
Pumpkinseed, *Lepomis gibbosus*	FT, M	Copper sulfate	125	1,660	-	Spear, 1977
Pumpkinseed, *Lepomis gibbosus*	FT, M	Copper sulfate	125	1,740	-	Spear, 1977
Bluegill, *Lepomis macrochirus*	FT, M	Copper sulfate	45	1,100	-	Benoit, 1975
Bluegill, *Lepomis macrochirus*	FT, M	Copper sulfate	200	8,300	-	Geckler, et al. 1976
Bluegill, *Lepomis macrochirus*	FT, M	Copper sulfate	200	10,000	-	Geckler, et al. 1976
Bluegill, *Lepomis macrochirus*	S, U	Copper chloride	43	1,250	-	Patrick, et al. 1968
Bluegill, *Lepomis macrochirus*	S, U	Copper sulfate	20	660	-	Pickering & Henderson, 1966

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/l as $CaCO_3$)	LC50/EC50 (µg/l)**	Species Mean Acute Value (µg/l)**	Reference
Bluegill, *Lepomis macrochirus*	S, U	Copper sulfate	360	10,200	-	Pickering & Henderson, 1966
Bluegill, *Lepomis macrochirus*	FT, M	Copper sulfate	35	2,400	-	O'Hara, 1971
Largemouth bass, *Micropterus salmoides*	R, U	-	100	6,970	-	Birge & Black, 1979
			SALTWATER SPECIES			
Polychaete worm, *Neanthes arenaceodentata*	FT, M	Copper nitrate	-	77	-	Pesch & Morgan, 1978
Polychaete worm, *Neanthes arenaceodentata*	FT, M	Copper nitrate	-	200	124	Pesch & Morgan, 1978
Polychaete worm, *Nereis diversicolor*	S, U	Copper sulfate	-	200	-	Jones, et al. 1976
Polychaete worm, *Nereis diversicolor*	S, U	Copper sulfate	-	445	-	Jones, et al. 1976
Polychaete worm, *Nereis diversicolor*	S, U	Copper sulfate	-	480	-	Jones, et al. 1976
Polychaete worm, *Nereis diversicolor*	S, U	Copper sulfate	-	410	364	Jones, et al. 1976
Polychaete worm, *Phyllodoce maculata*	S, U	Copper sulfate	-	120	120	McLusky & Phillips, 1975
Pacific oyster, *Crassostrea gigas*	FT, M	Copper sulfate	-	560	560	Okazaki, 1976
American oyster, *Crassostrea virginica*	S, U	Copper chloride	-	128	128	Calabrese, et al. 1973
Black abalone, *Haliotis cracherodii*	S, U	Copper sulfate	-	50	50	Martin, et al. 1977
Red abalone, *Haliotis rufescens*	S, U	Copper sulfate	-	65	-	Martin, et al. 1977

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/l as $CaCO_3$)	LC50/EC50 (µg/l)**	Species Mean Acute Value (µg/l)**	Reference
Red abalone (larva), *Haliotis rufescens*	S, U	Copper sulfate	-	114	86	Martin, et al. 1977
Soft shelled clam, *Mya arenaria*	S, U	Copper chloride	-	39	39	Eisler, 1977
Calanoid copepod, *Acartia clausi*	S, U	Copper chloride	-	52	52	U.S. EPA, 1980
Calanoid copepod, *Acartia tonsa*	S, U	Copper chloride	-	17	-	Sosnowski & Gentile, 1978
Calanoid copepod, *Acartia tonsa*	S, U	Copper chloride	-	55	-	Sosnowski & Gentile, 1978
Calanoid copepod, *Acartia tonsa*	S, U	Copper chloride	-	31	31	Sosnowski & Gentile, 1978
Copepod, *Eurytemora affinis*	S, U	Copper chloride	-	526	526	U.S. EPA, 1980
Copepod, *Pseudodiaptomus coronatus*	S, U	Copper chloride	-	138	138	U.S. EPA, 1980
Copepod, *Tigriopus japonicus*	S, U	Copper chloride	-	487	487	U.S. EPA, 1980
Mysid shrimp, *Mysidopsis bahia*	FT, M	Copper nitrate	-	181	181	U.S. EPA, 1980
Mysid shrimp, *Mysidopsis bigelowi*	FT, M	Copper nitrate	-	141	141	U.S. EPA, 1980
American lobster (larva), *Homarus americanus*	S, U	Copper nitrate	-	48	-	Johnson & Gentile, 1979
American lobster (adult), *Homarus americanus*	S, U	Copper sulfate	-	100	69	McLeese, 1974
Brown shrimp (larva), *Crangon crangon*	S, U	Copper sulfate	-	330	330	Connor, 1972

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/l as $CaCO_3$)	LC50/EC50 (µg/l)**	Species Mean Acute Value (µg/l)**	Reference
Shore crab (larva), *Carcinus maenus*	S, U	Copper sulfate	-	600	600	Connor, 1972
Florida pompano, *Trachinotus carolinus*	S, U	Copper sulfate	-	360	-	Birdsong & Avavit, 1971
Florida pompano, *Trachinotus carolinus*	S, U	Copper sulfate	-	380	-	Birdsong & Avavit, 1971
Florida pompano, *Trachinotus carolinus*	S, U	Copper sulfate	-	510	412	Birdsong & Avavit, 1971
Atlantic silverside (larva), *Menidia menidia*	FT, M	Copper nitrate	-	136 (7)***	136	U.S. EPA, 1980
Summer flounder (embryo), *Paralichthys dentatus*	FT, M	Copper chloride	-	28 (3)***	28	U.S. EPA, 1980
Winter flounder (embryo), *Pseudopleuronectes americanus*	FT, M	Copper nitrate	-	129 (9)***	129	U.S. EPA, 1980

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* S = static, FT = flow-through, R = renewal, U = unmeasured, M = measured

** Results are expressed as copper, not as the compound.

***Arithmetic mean of (N) results.

Freshwater:

Acute toxicity vs. hardness

Cladoceran, *Daphnia magna*: slope = 1.34, intercept = -2.64, r = 0.80, p = 0.01, N = 10

Cladoceran, *Daphnia pulicaria*: slope = 0.70, intercept = -0.40, r = 0.94, p = 0.01, N = 8

Chinook salmon, *Oncorhynchus tshawytscha*: slope = 0.67, intercept = 0.93, r = 0.93, p = 0.01, N = 8

Cutthroat trout, *Salmo clarki*: slope = 0.88, intercept = 0.79, r = 0.78, p = 0.01. N = 9

Table 1. (Continued)

Rainbow trout, *Salmo gairdneri*: slope = 0.87, intercept = 0.33, r = 0.78, p = 0.01, N = 39

Fathead minnow, *Pimephales promelas*: slope = 1.12, intercept = 0.38, r = 0.96, p = 0.01, N = 15

Bluegill, *Lepomis macrochirus*: slope = 1.00, intercept = 3.60, r = 0.95, p = 0.01, N = 7

Arithmetic mean acute slope = 0.94

Table 2. Chronic values for copper

Species	Test*	Chemical	Hardness (mg/l as CaCO$_3$)	Limits (µg/l)**	Chronic Value (µg/l)**	Reference
			FRESHWATER SPECIES			
Snail, *Campeloma decisum*	LC	Copper sulfate	45	8-14.8	10.9	Arthur & Leonard, 1970
Snail, *Physa integra*	LC	Copper sulfate	45	8-14.8	10.9	Arthur & Leonard, 1970
Cladoceran, *Daphnia magna*	LC	Copper chloride	51	11.4-16.3	13.6	Chapman, et al. Manuscript
Cladocerarn, *Daphnia magna*	LC	Copper chloride	104	20-43	29.0	Chapman, et al. Manuscript
Cladoceran, *Daphnia magna*	LC	Copper chloride	211	7.2-12.6	9.5	Chapman, et al. Manuscript
Scud, *Gammarus pseudolimnaeus*	LC	Copper sulfate	45	4.6-8	6.1	Arthur & Leonard, 1970
Rainbow trout, *Salmo gairdneri*	ELS	Copper sulfate	45.4	11.4-31.7	19	McKim, et al. 1978
Brown trout, *Salmo trutta*	ELS	Copper sulfate	45.4	22.0-43.2	30.8	McKim, et al. 1978
Brook trout, *Salvelinus fontinalis*	LC	Copper sulfate	45	9.5-17.4	12.9	McKim & Benoit, 1971
Brook trout, *Salvelinus fontinalis*	ELS	Copper sulfate	45.4	22.3-43.5	31.1	McKim, et al. 1978
Brook trout, *Salvelinus fontinalis*	ELS	Copper sulfate	37.5	3-5	3.9	Sauter, et al. 1976
Brook trout, *Salvelinus fontinalis*	ELS	Copper sulfate	187	5-8	6.3	Sauter, et al. 1976
Lake trout, *Salvelinus namaycush*	ELS	Copper sulfate	45.4	22.0-42.3	30.5	McKim, et al. 1978

Table 2. (Continued)

Species	Test*	Chemical	Hardness (mg/l as $CaCO_3$)	Limits (µg/l)**	Chronic Value (µg/l)**	Reference
Northern pike, *Esox lucius*	ELS	Copper sulfate	45.4	34.9-104.4	60.4	McKim, et al. 1978
Bluntnose minnow, *Pimephales notatus*	LC	Copper sulfate	194	4.3-18	8.8	Horning & Neiheisel, 1979
Fathead minnow, *Pimephales promelas*	LC	Copper sulfate	198	14.5-33	21.9	Mount, 1968
Fathead minnow, *Pimephales promelas*	LC	Copper sulfate	30	10.6-18.4	14.0	Mount & Stephan, 1969
Fathead minnow, *Pimephales promelas*	LC	Copper sulfate	200	24-32	27.7	Pickering, et al. 1977
Fathead minnow, *Pimephales promelas*	ELS	-	45	13.1-26.2	18.5	Lind, et al. Manuscript
White sucker, *Catostomus commersoni*	ELS	Copper sulfate	45.4	12.9-33.8	20.9	McKim, et al. 1978
Channel catfish, *Ictalurus punctatus*	ELS	Copper sulfate	36	12-18	14.7	Sauter, et al. 1976
Channel catfish, *Ictalurus punctatus*	ELS	Copper sulfate	186	13-19	15.7	Sauter, et al. 1976
Bluegill, *Lepomis macrochirus*	LC	Copper sulfate	45	21-40	29.0	Benoit, 1975
Walleye, *Stizostedion vitreum*	ELS	Copper sulfate	35	13-21	16.5	Sauter, et al. 1976
			SALTWATER SPECIES			
Mysid shrimp, *Mysidopsis bahia*	LC	Copper nitrate	54	38-77	54	U.S. EPA, 1980

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* LC = life cycle or partial life cycle; ELS = early life stage

**Results are expressed as copper, not as the compound.

Table 2. (Continued)

Acute-Chronic Ratios

Species	Hardness (mg/l as $CaCO_3$)	Acute Value (µg/l)	Chronic Value (µg/l)	Ratio
Snail, *Campeloma decisum*	45	1,700	10.9	156
Snail, *Physa integra*	45	39	10.9	3.6
Cladoceran, *Daphnia magna*	57	26	13.6	1.9
Cladoceran, *Daphnia magna*	104	34	29.0	1.2
Cladoceran, *Daphnia magna*	211	69	9.5	7.3
Scud, *Gammarus pseudolimnaeus*	45	20	6.1	3.3
Brook trout, *Salvelinus fontinalis*	45	100	12.9	7.8
Bluntnose minnow, *Pimephales notatus*	194	233	8.8	26
Fathead minnow, *Pimephales promelas*	198	430	21.9	20
Fathead minnow, *Pimephales promelas*	30	75	14.0	5.4
Fathead minnow, *Pimephales promelas*	200	475	27.7	17
Fathead minnow, *Pimephales promelas*	45	108	18.5	5.8
Bluegill, *Lepomis macrochirus*	45	1,100	29.0	38
Mysid shrimp, *Mysidopsis bahia*	-	181	54	3.4

Table 2. (Continued)

Freshwater Species Mean Chronic Values

Rank*	Species	Species Mean Chronic Value (µg/l)
15	Northern pike, *Esox lucius*	60.4
14	Brown trout, *Salmo trutta*	30.8
13	Lake trout *Salvelinus namaycush*	30.5
12	Bluegill, *Lepomis macrochirus*	29.0
11	White sucker, *Catostomus commersoni*	20.9
10	Fathead minnow, *Pimephales promelas*	19.9
9	Rainbow trout, *Salmo gairdneri*	19.0
8	Walleye, *Stizostedion vitreum*	16.5
7	Cladoceran, *Daphnia magna*	15.5
6	Channel catfish, *Ictalurus punctatus*	15.2
5	Snail, *Physa integra*	10.9
4	Snail, *Campeloma decisum*	10.9
3	Brook trout, *Salvelinus fontinalis*	10.0

Table 2. (Continued)

Rank*	Species	Species Mean Chronic Value (µg/l)
2	Bluntnose minnow, *Pimephales notatus*	8.8
1	Scud, *Gammarus pseudolimnaeus*	6.1

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* Ranked from least sensitive to most sensitive based on species mean chronic value.

Freshwater Final Chronic Value = 5.56 µg/l

Table 3. Species mean acute intercepts and values and acute-chronic ratios for copper

Rank*	Species	Species Mean Acute Intercept (µg/l)	Species Mean Acute-Chronic Ratio
	FRESHWATER SPECIES		
45	Stonefly, *Acroneuria lycorias*	260	-
44	Caddisfly, Unidentified	150	-
43	White perch, *Morone americanus*	148	-
42	American eel, *Anguilla rostrata*	145	-
41	Damselfly, Unidentified	117	-
40	Largemouth bass, *Micropterus salmoides*	91.8	-
39	Bluegill, *Lepomis macrochirus*	47.9	38
38	Snail, *Campeloma decisum*	46.5	156
37	Crayfish, *Orconectes rusticus*	35.2	-
36	Scud, *Gammarus* sp.	23.1	-
35	Snail, *Amnicola* sp.	22.9	-
34	Pumpkinseed, *Lepomis gibbosus*	21.8	-
33	Banded killifish, *Fundulus diaphanus*	20.1	-
32	Carp, *Cyprinus carpio*	18.9	-

Table 3. (Continued)

Rank*	Species	Species Mean Acute Intercept (µg/l)	Species Mean Acute-Chronic Ratio
31	Rotifer, *Philodina acuticornis*	14.4	-
30	Striped bass, *Morone saxatilis*	10.1	-
29	Striped shiner, *Notropis chrysocephalus*	8.41	-
28	Orangethroat darter, *Etheostoma spectabile*	5.81	-
27	Longfin dace, *Agosia chrysogaster*	5.37	-
26	Flagfish, *Jordanella floridae*	5.00	-
25	Atlantic salmon, *Salmo salar*	4.95	-
24	Goldfish, *Carassius auratus*	3.97	-
23	Fathead minnow, *Pimephales promelas*	3.29	10.1
22	Brook trout, *Salvelinus fontinalis*	2.80	7.8
21	Worm, *Nais* sp.	2.28	-
20	Rainbow darter, *Etheostoma caeruleum*	2.20	-
19	Blacknose dace, *Rhinichthys atratulus*	2.20	-
18	Brown bullhead, *Ictalurus nebulosus*	2.13	-

Table 3. (Continued)

Rank*	Species	Species Mean Acute Intercept (µg/l)	Species Mean Acute-Chronic Ratio
17	Creek chub, *Semotilus atromaculatus*	2.13	-
16	Guppy, *Poecilia reticulata*	2.12	-
15	Stoneroller, *Campostoma anomalum*	1.99	-
14	Bluntnose minnow, *Pimephales notatus*	1.83	26
13	Cutthroat trout, *Salmo clarki*	1.68	-
12	Snail, *Gyraulus circumstriatus*	1.42	-
11	Worm, *Limnodrilus hoffmeisteri*	1.34	-
10	Coho salmon, *Oncorhynchus kisutch*	1.23	-
9	Snail, *Physa integra*	1.07	3.6
8	Rainbow trout, *Salmo gairdneri*	1.02	-
7	Chinook salmon, *Oncorhynchus tshawytscha*	0.91	-
6	Snail, *Physa heterostropha*	0.91	-
5	Midge, Unidentified	0.76	-
4	Scud, *Gammarus pseudolimnaeus*	0.55	3.3

Table 3. (Continued)

Rank*	Species	Species Mean Acute Intercept (µg/l)	Species Mean Acute-Chronic Ratio
3	Cladoceran, *Daphnia magna*	0.43	2.6
2	Cladoceran, *Daphnia pulex*	0.28	-
1	Cladoceran, *Daphnia pulicaria*	0.23	-

Rank*	Species	Species Mean Acute Value (µg/l)	Species Mean Acute-Chronic Ratio
	SALTWATER SPECIES		
22	Shore carb, *Carcinus maenus*	600	-
21	Pacific oyster, *Crassostrea gigas*	560	-
20	Copepod, *Eurytemora affinis*	526	-
19	Copepod, *Tigriopus japonicus*	487	-
18	Florida pompano, *Trachinotus carolinus*	412	-
17	Polychaete worm, *Nereis diversicolor*	364	-
16	Brown shrimp, *Crangon crangon*	330	-
15	Mysid shrimp, *Mysidopsis bahia*	181	3.4
14	Mysid shrimp, *Mysidopsis bigelowi*	141	-

Table 3. (Continued)

Rank*	Species	Species Mean Acute Value (µg/l)	Species Mean Acute-Chronic Ratio
13	Copepod, *Pseudodiaptomus coronatus*	138	-
12	Atlantic silverside, *Menidia menidia*	136	-
11	Winter flounder, *Pseudopleuronectes americanus*	129	-
10	American oyster, *Crassostrea virginica*	128	-
9	Polychaete worm, *Neanthes arenaceodentata*	124	-
8	Polychaete worm, *Phyllodoce maculata*	120	-
7	Red abalone, *Haliotis rufescens*	86	-
6	American lobster, *Homarus americanus*	69	-
5	Calanoid copepod, *Acartia clausi*	52	-
4	Black abalone, *Haliotis cracherodii*	50	-
3	Soft shelled clam, *Mya arenaria*	39	-
2	Calanoid copepod, *Acartia tonsa*	31	-
1	Summer flounder, *Paralichthys dentatus*	28	-

Table 3. (Continued)

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* Ranked from least sensitive to most sensitive based on species mean acute value or intercept.

Freshwater

Final Acute Intercept = 0.29 µg/l

Natural logarithm of 0.29 = -1.23

Acute slope = 0.94 (see Table 1)

Final Acute Equation = $e^{(0.94[\ln(\text{hardness})]-1.23)}$

Saltwater

Final Acute Value = 22.9 µg/l

Acute-Chronic Ratio = 5.78 (see text)

Final Chronic Value = (22.9 µg/l)/5.78 = 4.0 µg/l

Table 4. Plant values for copper

Species	Effect	Result (µg/l)	Reference
	FRESHWATER SPECIES		
Alga, *Anabaena flos-aqua*	75% growth inhibition	200	Young & Lisk, 1972
Alga, *Anabaena variabilis*	Growth inhibition	100	Young & Lisk, 1972
Alga, *Anacystis nidulans*	Growth inhibiton	100	Young & Lisk, 1972
Alga, *Chlamydomonas* sp.	Growth reduction	8,000	Cairns, et al. 1978
Alga, *Chlorella pyrenoidosa*	Lag in growth	1	Steeman-Nielsen & Wium-Andersen, 1970
Alga, *Chlorella pyrenoidosa*	Growth inhibition	100	Steeman-Nielsen & Kamp-Nielsen, 1970
Alga, *Chlorella regularis*	Lag in growth	20	Sakaguchi, et al. 1977
Alga, *Chlorella* sp.	Photosynthesis inhibited	6.3	Gachter, et al. 1973
Alga, *Chlorella vulgaris*	Growth inhibition	200	Young & Lisk, 1972
Alga, *Chlorella vulgaris*	EC50 growth, 33 days	180	Rosko & Rachlin, 1977
Alga, *Chlorella vulgaris*	50% growth reduction	100-200	Stokes & Hutchinson, 1976
Alga, *Cyclotella meneghiniana*	Growth reduction	8,000	Cairns, et al. 1978
Alga, *Eudorina californica*	Growth inhibition	5,000	Young & Lisk, 1972
Alga, *Scenedesmus acuminatus*	40% growth reduction	300	Stokes & Hutchinson, 1976

Table 4. (Continued)

Species	Effect	Result (µg/l)	Reference
Alga, *Scenedesmus quadricauda*	Threshold toxicity	150	Bringman & Kuhn, 1959
Alga, *Scenedesmus quadricauda*	Growth reduction	8,000	Cairns, et al. 1978
Algae, Mixed culture	Significant reduction in photosynthesis	5	Elder & Horne, 1978
Blue green algae, Mixed culture	50% reduction in photosynthesis	25	Steeman-Nielsen & Bruun-Laursen, 1976
Diatom, *Nitzschia linearis*	120 hr EC50	795-815	Patrick, et al. 1968
Diatom, *Nitzschia palea*	Complete growth inhibition	5	Steeman-Nielsen & Wium-Anderson, 1970
Duckweed, *Lemna minor*	EC50, 7 day	119	Walbridge, 1977
Macrophyte, *Elodea canadensis*	50% reduction in photosynthetic O_2 production	150	Brown & Rattigan, 1979
Eurasian watermilfoil, *Myriophyllum spicatum*	50% root weight reduction	250	Stanley, 1974
Green alga, *Selenastrum capricornutum*	Growth reduction	50	Bartlett, et al. 1974
	SALTWATER SPECIES		
Alga, giant kelp, *Macrocystis pyrifera*	96 hr EC50 photosynthesis inactivation	100	Clendenning & North, 1959
Alga, *Thalassiosira pseudonana*	72 hr EC50 growth rate	5	Erickson, 1972

Table 4. (Continued)

Species	Effect	Result (µg/l)	Reference
Alga, *Amphidinium carteri*	14 day EC50 growth rate	<50	Erickson, et al. 1970
Alga, *Olisthodiscus luteus*	14 day EC50 growth rate	<50	Erickson, et al. 1970
Alga, *Skeletonema costatum*	14 day EC50 growth rate	50	Erickson, et al. 1970
Alga, *Nitschia closterium*	96 hr EC50 growth rate	33	Rosko & Rachlin, 1975
Alga, *Scrippsiella faeroense*	5 day EC50 growth rate	5	Saifullah, 1978
Alga, *Prorocentrum micans*	5 day EC50 growth rate	10	Saifullah, 1978
Alga, *Gymnodinium splendens*	5 day EC50 growth rate	20	Saifullah, 1978

Table 5. Residues for copper

Species	Tissue	Bioconcentration Factor	Duration (days)	Reference
FRESHWATER SPECIES				
Alga, *Chlorella regularis*	-	2,000	20 hrs	Sakaguchi, et al. 1977
Stonefly, *Pteronarcys californica*	-	203	14	Nehring, 1976
Fathead minnow (larva), *Pimephales promelas*	-	290	30	Lind, et al. Manuscript
Bluegill, *Lepomis macrochirus*	Muscle	0	660	Benoit, 1975
SALTWATER SPECIES				
Polychaete worm, *Cirriformia spirabracha*		250*	24	Milanovich, et al. 1976
Polychaete worm, *Neanthes arenaceodentata*	-	2,550*	28	Pesch & Morgan, 1978
Polychaete worm, *Nereis diversicolor*	-	203*	24	Jones, et al. 1976
Polychaete worm, *Phyllodoce maculata*	-	1,750*	21	McLusky & Phillips, 1975
Bay scallop, *Argopecten irradians*	-	3,310	112	Zaroogian, 1978
Bay scallop, *Argopecten irradians*	-	4,160	112	Zaroogian, 1978
American oyster, *Crassostrea virginica*	-	28,200	140	Shuster & Pringle, 1969
American oyster, *Crassostrea virginica*	-	20,700	140	Shuster & Pringle, 1969
Northern quahaug, *Mercenaria mercenaria*	-	88	70	Shuster & Pringle, 1968

Table 5. (Continued)

Species	Tissue	Bioconcentration Factor	Duration (days)	Reference
Soft shelled clam, *Mya arenaria*	-	3,300	35	Shuster & Pringle, 1968
Mussel, *Mytilus edulis*	-	208	112	U.S. EPA, 1980
Mussel, *Mytilus edulis*	-	108	112	U.S. EPA, 1980
Mussel, *Mytilus edulis*	-	90	14	Phillips, 1976
Mussel, *Mytilus galloprovincialis*	-	800	25	Majori & Petronio, 1973
Alga, *Dunaliella primolecta*	-	153*	25	Riley & Roth, 1971
Alga, *Dunaliella tertiolecta*	-	168*	25	Riley & Roth, 1971
Alga, *Chlamydomonas* sp.	-	135*	25	Riley & Roth, 1971
Alga, *Chlorella salina*	-	74*	25	Riley & Roth, 1971
Alga, *Stichococcus bacillaris*	-	156*	25	Riley & Roth, 1971
Alga, *Hemiselmis virescens*	-	273*	25	Riley & Roth, 1971
Alga, *Hemiselmis brunescens*	-	553*	25	Riley & Roth, 1971
Alga, *Olisthodiscus luteus*	-	182*	25	Riley & Roth, 1971
Alga, *Asterionella japonica*	-	309*	25	Riley & Roth, 1971
Alga, *Phaeodactylum tricornutum*	-	323*	25	Riley & Roth, 1971

Table 5. (Continued)

Species	Tissue	Bioconcentration Factor	Duration (days)	Reference
Alga, *Monochrysis lutheri*	-	138*	25	Riley & Roth, 1971
Alga, *Pseudopedinella pyriformis*	-	85*	25	Riley & Roth, 1971
Alga, *Heteromastix longifillis*	-	617*	25	Riley & Roth, 1971
Alga, *Micromonas squamata*	-	279*	25	Riley & Roth, 1971
Alga, *Tetraselmis tetrathele*	-	265*	25	Riley & Roth, 1971

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*Dry weight to wet weight conversion

Table 6. Other data for copper

Species	Duration	Effect	Result (µg/l)	Reference
		FRESHWATER SPECIES		
Annelid worm, *Aeolosoma headleyi*	48 hrs	LC50	2,600	Cairns, et al. 1978
Annelid worm, *Aeolosoma headleyi*	48 hrs	LC50	2,300	Cairns, et al. 1978
Annelid worm, *Aeolosoma headleyi*	48 hrs	LC50	2,000	Cairns, et al. 1978
Annelid worm, *Aeolosoma headleyi*	48 hrs	LC50	1,650	Cairns, et al. 1978
Annelid worm, *Aeolosoma headleyi*	48 hrs	LC50	1,000	Cairns, et al. 1978
Snail (embryo), *Amnicola* sp.	96 hrs	LC50	9,300	Rehwoldt, et al. 1973
Snail, *Goniobasis livescens*	48 hrs	LC50	860	Cairns, et al. 1976
Snail, *Lymnea emarginata*	48 hrs	LC50	300	Cairns, et al. 1976
Snail, *Nitrocris* sp.	48 hrs	LC50	3,000	Cairns, et al. 1978
Snail, *Nitrocris* sp.	48 hrs	LC50	2,400	Cairns, et al. 1978
Snail, *Nitrocris* sp.	48 hrs	LC50	1,000	Cairns, et al. 1978
Snail, *Nitrocris* sp.	48 hrs	LC50	300	Cairns, et al. 1978
Snail, *Nitrocris* sp.	48 hrs	LC50	210	Cairns, et al. 1978
Cladoceran, *Daphnia ambigua*	72 hrs	LC50	67.7	Winner & Farrell, 1976

Table 6. (Continued)

Species	Duration	Effect	Result (µg/l)	Reference
Cladoceran, *Daphnia magna*	48 hrs	LC50	60	Biesinger & Christensen, 1972
Cladoceran, *Daphnia magna*	48 hrs	LC50 (5 C)	90	Cairns, et al. 1978
Cladoceran, *Daphnia magna*	48 hrs	LC50 (10 C)	70	Cairns, et al. 1978
Cladoceran, *Daphnia magna*	48 hrs	LC50 (15 C)	40	Cairns, et al. 1978
Cladoceran, *Daphnia magna*	48 hrs	LC50 (25 C)	7	Cairns, et al. 1978
Cladoceran, *Daphnia magna*	Life cycle	Reduced number of young produced	10	Winner, et al. 1977
Cladoceran, *Daphnia magna*	Life cycle	Reduced number of young produced	10	Winner, et al. 1977
Cladoceran, *Daphnia magna*	Life cycle	Reduced productivity	27.7	Biesinger & Christensen, 1972
Cladoceran, *Daphnia magna*	Life cycle	Reduced productivity	28.2	Winner, et al. 1977
Cladoceran, *Daphnia magna*	Life cycle	Reduced productivity	28.2	Winner, et al. 1977
Cladoceran, *Daphnia magna*	Life cycle	Reduced productivity	28.2	Winner, et al. 1977
Cladoceran, *Daphnia magna*	Life cycle	Reduced productivity	49	Winner & Farrell, 1976
Cladoceran, *Daphnia magna*	Life cycle	Reduced number of young produced	10	Adema & DeGroot Van Zijl, 1972
Cladoceran, *Daphnia magna*	72 hrs	LC50	86.5	Winner & Farrell, 1976

Table 6. (Continued)

Species	Duration	Effect	Result (µg/l)	Reference
Cladoceran, *Daphnia magna*	72 hrs	LC50	88.0	Winner & Farrell, 1976
Cladoceran, *Daphnia magna*	72 hrs	LC50	85	Winner & Farrell, 1976
Cladoceran, *Daphnia magna*	72 hrs	LC50	81.5	Winner & Farrell, 1976
Cladoceran, *Daphnia magna*	72 hrs	LC50	81.4	Winner & Farrell, 1976
Cladoceran, *Daphnia magna*	72 hrs	LC50	85.3	Winner & Farrell, 1976
Cladoceran, *Daphnia magna*	29 hrs	Median survival time	12.7	Andrew, et al. 1977
Cladoceran, *Daphnia magna*	24 hrs	LC50	80	Bringman & Kuhn, 1977
Cladoceran, *Daphnia parvula*	72 hrs	LC50	57	Winner & Farrell, 1976
Cladoceran, *Daphnia parvula*	72 hrs	LC50	72	Winner & Farrell, 1976
Cladoceran, *Daphnia parvula*	Life cycle	Reduced productivity	49	Winner & Farrell, 1976
Cladoceran, *Daphnia pulex*	72 hrs	LC50	54	Winner & Farrell, 1976
Cladoceran, *Daphnia pulex*	72 hrs	LC50	86	Winner & Farrell, 1976
Cladoceran, *Daphnia pulex*	Life cycle	Reduced productivity	49	Winner & Farrell, 1976

Table 6. (Continued)

Species	Duration	Effect	Result (µg/l)	Reference
Cladoceran, *Daphnia pulex*	48 hrs	LC50 (5 C)	70	Cairns, et al. 1978
Cladoceran, *Daphnia pulex*	48 hrs	LC50 (10 C)	60	Cairns, et al. 1978
Cladoceran, *Daphnia pulex*	48 hrs	LC50 (15 C)	20	Cairns, et al. 1978
Cladoceran, *Daphnia pulex*	48 hrs	LC50 (25 C)	5.6	Cairns, et al. 1978
Cladoceran, *Daphnia pulicaria*	48 hrs	LC50 (TOC 14 mg/l)	55.5	Lind, et al. Manuscript
Cladoceran, *Daphnia pulicaria*	48 hrs	LC50 (TOC 13 mg/l)	55.3	Lind, et al. Manuscript
Cladoceran, *Daphnia pulicaria*	48 hrs	LC50 (TOC 13 mg/l)	53.3	Lind, et al. Manuscript
Cladoceran, *Daphnia pulicaria*	48 hrs	LC50 (TOC 28 mg/l)	97.2	Lind, et al. Manuscript
Cladoceran, *Daphnia pulicaria*	48 hrs	LC50 (TOC 34 mg/l)	199	Lind, et al. Manuscript
Cladoceran, *Daphnia pulicaria*	48 hrs	LC50 (TOC 34 mg/l)	627	Lind, et al. Manuscript
Cladoceran, *Daphnia pulicaria*	48 hrs	LC50 (TOC 32 mg/l)	213	Lind, et al. Manuscript
Cladoceran, *Daphnia pulicaria*	48 hrs	LC50 (TOC 32 mg/l)	165	Lind, et al. Manuscript
Cladoceran, *Daphnia pulicaria*	48 hrs	LC50 (TOC 12 mg/l)	35.5	Lind, et al. Manuscript
Cladoceran, *Daphnia pulicaria*	48 hrs	LC50 (TOC 13 mg/l)	78.8	Lind, et al. Manuscript

Table 6. (Continued)

Species	Duration	Effect	Result (µg/l)	Reference
Cladoceran, *Daphnia pulicaria*	48 hrs	LC50 (TOC 28 mg/l)	113	Lind, et al. Manuscript
Cladoceran, *Daphnia pulicaria*	48 hrs	LC50 (TOC 25 mg/l)	76.4	Lind, et al. Manuscript
Cladoceran, *Daphnia pulicaria*	48 hrs	LC50 (TOC 13 mg/l)	84.7	Lind, et al. Manuscript
Cladoceran, *Daphnia pulicaria*	48 hrs	LC50 (TOC 21 mg/l)	184	Lind, et al. Manuscript
Cladoceran, *Daphnia pulicaria*	48 hrs	LC50 (TOC 34 mg/l)	240	Lind, et al. Manuscript
Cladoceran, *Daphnia ambigua*	Life cycle	Reduced productivity	49	Winner & Farrell, 1976
Scud, *Gammarus lacustris*	96 hrs	LC50	1,500	Nebeker & Gaufin, 1964
Mayfly, *Ephemerella subvaria*	48 hrs	LC50	320	Warnick & Bell, 1969
Mayfly, *Ephemerella grandis*	14 days	LC50	180-200	Nehring, 1976
Stonefly, *Pteronarcys californica*	14 days	LC50	10,100- 13,900	Nehring, 1976
Caddisfly, *Hydropsyche betteni*	14 days	50% survival	32,000	Warnick & Bell, 1969
Midge, *Tanytarsus dissimilis*	10 days	LC50	16.3	Anderson, et al. 1980
Crayfish, *Orconectes rusticus*	17 days	Survival of newly hatched young	125	Hubshman, 1967
Rotifer, *Philodina acuticornis*	48 hrs	LC50	1,300	Cairns, et al. 1978

Table 6. (Continued)

Species	Duration	Effect	Result (µg/l)	Reference
Rotifer, *Philodina acuticornis*	48 hrs	LC50	1,200	Cairns, et al. 1978
Rotifer, *Philodina acuticornis*	48 hrs	LC50	1,130	Cairns, et al. 1978
Rotifer, *Philodina acuticornis*	48 hrs	LC50	1,000	Cairns, et al. 1978
Rotifer, *Philodina acuticornis*	48 hrs	LC50	950	Cairns, et al. 1978
Coho salmon, *Oncorhynchus kisutch*	96 hrs	Reduced survival on transfer to seawater	30	Lorz & McPherson, 1976
Coho salmon, *Oncorhynchus kisutch*	30 days	LC50	360	Holland, et al. 1960
Coho salmon, *Oncorhynchus kisutch*	72 hrs	LC50	280	Holland, et al. 1960
Coho salmon, *Oncorhynchus kisutch*	72 hrs	LC50	370	Holland, et al. 1960
Coho salmon, *Oncorhynchus kisutch*	72 hrs	LC50	190	Holland, et al. 1960
Coho salmon, *Oncorhynchus kisutch*	72 hrs	LC50	480	Holland, et al. 1960
Coho salmon, *Oncorhynchus kisutch*	72 hrs	LC50	440	Holland, et al. 1960
Coho salmon, *Oncorhynchus kisutch*	72 hrs	LC50	460	Holland, et al. 1960
Coho salmon, *Oncorhynchus kisutch*	72 hrs	LC50	480	Holland, et al. 1960
Coho salmon, *Oncorhynchus kisutch*	72 hrs	LC50	560	Holland, et al. 1960

Table 6. (Continued)

Species	Duration	Effect	Result (µg/l)	Reference
Coho salmon, Oncorhynchus kisutch	72 hrs	LC50	780	Holland, et al. 1960
Coho salmon, Oncorhynchus kisutch	72 hrs	LC50	510	Holland, et al. 1960
Coho salmon, Oncorhynchus kisutch	72 hrs	LC50	520	Holland, et al. 1960
Coho salmon, Oncorhynchus kisutch	72 hrs	LC50	480	Holland, et al. 1960
Sockeye salmon, Oncorhynchus nerka	24 hrs	Significant change in corticosteriod (stress)	64	Donaldson & Dye, 1975
Chinook salmon, Oncorhynchus tshawytscha	5 days	LC50	178	Holland, et al. 1960
Chinook salmon, Oncorhynchus tshawytscha	26 days	Reduced survival and growth of sac fry	21	Hazel & Meith, 1970
Chinook salmon (alevin), Oncorhynchus tshawytscha	200 hrs	LC50	20	Chapman, 1978
Chinook salmon (alevin), Oncorhynchus tshawytscha	200 hrs	LC10	15	Chapman, 1978
Chinook salmon (swim-up), Oncorhynchus tshawytscha	200 hrs	LC50	19	Chapman, 1978
Chinook salmon (swim-up), Oncorhynchus tshawytscha	200 hrs	LC10	14	Chapman, 1978
Chinook salmon (parr), Oncorhynchus tshawytscha	200 hrs	LC50	30	Chapman, 1978
Chinook salmon (parr), Oncorhynchus tshawytscha	200 hrs	LC10	17	Chapman, 1978
Chinook salmon (smolt), Oncorhynchus tshawytscha	200 hrs	LC50	26	Chapman, 1978

Table 6. (Continued)

Species	Duration	Effect	Result (µg/l)	Reference
Chinook salmon (smolt), *Oncorhynchus tshawytscha*	200 hrs	LC10	18	Chapman, 1978
Chinook salmon, *Oncorhynchus tshawytscha*	72 hrs	LC50	190	Holland, 1960
Rainbow trout, *Salmo gairdneri*	96 hrs	LC50	516*	Howarth & Sprague, 1978
Rainbow trout, *Salmo gairdneri*	96 hrs	LC50	309*	Howarth & Sprague, 1978
Rainbow trout, *Salmo gairdneri*	96 hrs	LC50	111*	Howarth & Sprague, 1978
Rainbow trout, *Salmo gairdneri*	2 hrs	Depressed olfactory response	8	Hara, et al. 1976
Rainbow trout, *Salmo gairdneri*	7 days	LC50	44	Lloyd, 1961
Rainbow trout, *Salmo gairdneri*	21 days	Median period of survival	40	Grande, 1966
Rainbow trout, *Salmo gairdneri*	10 days	Depressed feeding rate and growth	75	Lett, et al. 1976
Rainbow trout, *Salmo gairdneri*	7 days	Median period of survival	44	Lloyd, 1961
Rainbow trout (alevin), *Salmo gairdneri*	186 hrs	LC50	26	Chapman, in press
Rainbow trout (alevin), *Salmo gairdneri*	186 hrs	LC10	19	Chapman, in press
Rainbow trout (swim-up), *Salmo gairdneri*	200 hrs	LC50	17	Chapman, in press
Rainbow trout (swim-up), *Salmo gairdneri*	200 hrs	LC10	9	Chapman, in press

Table 6. (Continued)

Species	Duration	Effect	Result (µg/l)	Reference
Rainbow trout (parr), *Salmo gairdneri*	200 hrs	LC50	15	Chapman, In press
Rainbow trout (parr), *Salmo gairdneri*	200 hrs	LC10	8	Chapman, In press
Rainbow trout (smolt), *Salmo gairdneri*	200 hrs	LC50	21	Chapman, In press
Rainbow trout (smolt), *Salmo gairdneri*	200 hrs	LC10	7	Chapman, In press
Rainbow trout (smolt), *Salmo gairdneri*	>10 days	Threshold LC50	94	Fogels & Sprague, 1977
Rainbow trout (smolt), *Salmo gairdneri*	14 days	LC50	870	Calamari & Marchetti, 1973
Rainbow trout (fry), *Salmo gairdneri*	1 hr	Avoidance behavior	0.1	Folmar, 1976
Rainbow trout (fry), *Salmo gairdneri*	24 hrs	LC50	950	Cairns, et al. 1978
Rainbow trout (fry), *Salmo gairdneri*	24 hrs	LC50	430	Cairns, et al. 1978
Rainbow trout (fry), *Salmo gairdneri*	24 hrs	LC50	150	Cairns, et al. 1978
Rainbow trout (fry), *Salmo gairdneri*	96 hrs	LC50 (field)	253	Hale, 1977
Rainbow trout (fry), *Salmo gairdneri*	96 hrs	LC50	250-680	Lett, et al. 1976
Rainbow trout (fry), *Salmo gairdneri*	48 hrs	LC50 (field)	70	Calamari & Marchetti, 1975
Rainbow trout (fry), *Salmo gairdneri*	96 hrs	LC50	250	Goettl, et al. 1972

Table 6. (Continued)

Species	Duration	Effect	Result (µg/l)	Reference
Rainbow trout (fry), *Salmo gairdneri*	24 hrs	LC50	140	Shaw & Brown, 1974
Rainbow trout (fry), *Salmo gairdneri*	24 hrs	LC50	130	Shaw & Brown, 1974
Rainbow trout (fry), *Salmo gairdneri*	72 hrs	LC50	580	Brown, et al. 1974
Rainbow trout, *Salmo gairdneri*	>15 days	Threshold LC50	19	Miller & McKay, 1980
Rainbow trout, *Salmo gairdneri*	>15 days	Threshold LC50	54	Miller & McKay, 1980
Rainbow trout, *Salmo gairdneri*	>15 days	Threshold LC50	48	Miller & McKay, 1980
Rainbow trout, *Salmo gairdneri*	>15 days	Threshold LC50	78	Miller & McKay, 1980
Rainbow trout, *Salmo gairdneri*	>15 days	Threshold LC50	18	Miller & McKay, 1980
Rainbow trout, *Salmo gairdneri*	>15 days	Threshold LC50	96	Miller & McKay, 1980
Rainbow trout, *Salmo gairdneri*	48 hrs	LC50	500	Brown, 1968
Rainbow trout, *Salmo gairdneri*	48 hrs	LC50	750	Brown & Dalton, 1970
Rainbow trout, *Salmo gairdneri*	48 hrs	LC50	150	Cope, 1966
Rainbow trout, *Salmo gairdneri*	72 hrs	LC50	1,100	Lloyd, 1961
Rainbow trout, *Salmo gairdneri*	48 hrs	LC50	270	Herbert & Vandyke, 1964

Table 6. (Continued)

Species	Duration	Effect	Result (µg/l)	Reference
Atlantic salmon, Salmo salar	7 days	Incipient lethal level	48	Sprague, 1964
Atlantic salmon, Salmo salar	7 days	Incipient lethal level	32	Sprague & Ramsay, 1965
Atlantic salmon, Salmo salar	21 days	Median period of survival	40	Grande, 1966
Atlantic salmon, Salmo salar	27-38 hrs	Median period of survival	50	Zitko & Carson, 1976
Brown trout, Salmo trutta	21 days	Median period of survival	45	Grande, 1966
Brook trout, Salvelinus fontinalis	24 hrs	Significant change in cough rate	9	Drummond, et al. 1973
Brook trout, Salvelinus fontinalis	21 days	Significant changes in blood chemistry	23	McKim, et al. 1970
Brook trout, Salvelinus fontinalis	337 days	Significant changes in blood chemistry	17.4	McKim, et al. 1970
Stoneroller, Campostonia anonealum	96 hrs	LC50	1,400	Geckler, et al. 1976
Goldfish, Carassius auratus	24 hrs	LC50	2,700	Cairns, et al. 1978
Goldfish, Carassius auratus	24 hrs	LC50	2,900	Cairns, et al. 1978
Goldfish, Carassius auratus	24 hrs	LC50	1,510	Cairns, et al. 1978
Golden shiner, Notemigonius crysoleucas	24 hrs	LC50	330	Cairns, et al. 1978
Golden shiner, Notemigonius crysoleucas	24 hrs	LC50	230	Cairns, et al. 1978
Golden shiner, Notemigonius crysoleucas	24 hrs	LC50	270	Cairns, et al. 1978

Table 6. (Continued)

Species	Duration	Effect	Result (µg/l)	Reference
Striped shiner, *Notropis chrysocephales*	96 hrs	LC50	8,400	Geckler, et al. 1976
Striped shiner, *Notropis chrysocephales*	96 hrs	LC50	16,000	Geckler, et al. 1976
Striped shiner, *Notropis chrysocephales*	96 hrs	LC50	3,400	Geckler, et al. 1976
Striped shiner, *Notropis chrysocephales*	96 hrs	LC50	4,000	Geckler, et al. 1976
Striped shiner, *Notropis chrysocephales*	96 hrs	LC50	5,000	Geckler, et al. 1976
Striped shiner, *Notropis chrysocephales*	96 hrs	Decrease blood osmolarity	2,500	Lewis & Lewis, 1971
Bluntnose minnow, *Pimephales notatus*	48 hrs	LC50 (21 tests)	750- 21,000	Geckler, et al. 1976
Bluntnose minnow, *Pimephales notatus*	96 hrs	LC50 (6 tests)	1,100- 20,000	Geckler, et al. 1976
Fathead minnow, *Pimephales promelas*	96 hrs	LC50 (21 tests)	1,600- 21,000	Brungs, et al. 1976
Fathead minnow, *Pimephales promelas*	96 hrs	LC50 (36 tests)	<650 23,600	Geckler, et al. 1976
Fathead minnow, *Pimephales promelas*	96 hrs	LC50 (7 tests)	740- 13,000	Geckler, et al. 1976
Fathead minnow, *Pimephales promelas*	96 hrs	LC50 (TOC = 12 mg/l)	436	Lind, et al. Manuscript
Fathead minnow, *Pimephales promelas*	96 hrs	LC50 (TOC = 13 mg/l)	516	Lind, et al. Manuscript

Table 6. (Continued)

Species	Duration	Effect	Result (µg/l)	Reference
Fathead minnow, Pimephales promelas	96 hrs	LC50 (TOC = 36 mg/l)	1,586	Lind, et al. Manuscript
Fathead minnow, Pimephales promelas	96 hrs	LC50 (TOC = 28 mg/l)	1,129	Lind, et al. Manuscript
Fathead minnow, Pimephales promelas	96 hrs	LC50 (TOC = 15 mg/l)	550	Lind, et al. Manuscript
Fathead minnow, Pimephales promelas	96 hrs	LC50 (TOC = 34 mg/l)	1,001	Lind, et al. Manuscript
Fathead minnow, Pimephales promelas	96 hrs	LC50 (TOC = 30 mg/l)	2,050	Lind, et al. Manuscript
Fathead minnow, Pimephales promelas	96 hrs	LC50 (TOC = 30 mg/l)	2,336	Lind, et al. Manuscript
Fathead minnow, Pimephales promelas	Life cycle	Chronic limits	66-120	Brungs, et al. 1976
Creek chub, Semotilus atromaculatus	96 hrs	LC50	11,500	Geckler, et al. 1976
Creek chub, Semotilus atromaculatus	96 hrs	LC50	1,100	Geckler, et al. 1976
Brown bullhead, Ictalurus nebulosus	96 hrs	LC50	11,000	Geckler, et al. 1976
Channel catfish, Ictalurus punctatus	94 hrs	Decreased blood osmolarity	2,500	Lewis & Lewis, 1971
Channel catfish, Ictalurus punctatus	24 hrs	LC50	1,730	Cairns, et al. 1978
Channel catfish, Ictalurus punctatus	24 hrs	LC50	2,600	Cairns, et al. 1978
Channel catfish, Ictalurus punctatus	24 hrs	LC50	3,100	Cairns, et al. 1978

Table 6. (Continued)

Species	Duration	Effect	Result (µg/l)	Reference
Flagfish, *Jordanella floridae*	10 days	LC50	680	Fogels & Sprague, 1977
Mosquitofish, *Gambusia affinis*	96 hrs	LC50 (750 mg/l turbidity)	75,000	Wallen, et al. 1957
Guppy, *Poecilia reticulata*	24 hrs	LC50	1,250	Minicucci, 1971
Rainbow darter, *Etheostema caeruleum*	96 hrs	LC50	4,300	Geckler, et al. 1976
Rainbow darter, *Etheostema caeruleum*	96 hrs	LC50	5,900	Geckler, et al. 1976
Rainbow darter, *Etheostema caeruleum*	96 hrs	LC50	2,800	Geckler, et al. 1976
Johnny darter, *Etheostema nigruni*	96 hrs	LC50	6,800	Geckler, et al. 1976
Orangethroat darter, *Etheostoma spectabile*	96 hrs	LC50	9,800	Geckler, et al. 1976
Orangethroat darter, *Etheostoma spectabile*	96 hrs	LC50	7,900	Geckler, et al. 1976
Orangethroat darter, *Etheostoma spectabile*	96 hrs	LC50	5,400	Geckler, et al. 1976
Orangethroat darter, *Etheostoma spectabile*	96 hrs	LC50	5,800	Geckler, et al. 1976
Rock bass, *Ambloplites reipestris*	96 hrs	LC50	1,432	Lind, et al. Manuscript
Bluegill, *Lepomis macrochirus*	24-36 hrs	Altered oxygen consumption rates	300	O'Hara, 1971
Bluegill, *Lepomis macrochirus*	48 hrs	LC50	2,800	Cope, 1966

Table 6. (Continued)

Species	Duration	Effect	Result (µg/l)	Reference
Bluegill, *Lepomis macrochirus*	96 hrs	LC50	16,000	Geckler, et al. 1976
Bluegill, *Lepomis macrochirus*	96 hrs	LC50	17,000	Geckler, et al. 1976
Bluegill, *Lepomis macrochirus*	96 hrs	LC50	740	Trama, 1956
Bluegill, *Lepomis macrochirus*	96 hrs	LC50	1,800	Turnbull, et al. 1954
		SALTWATER SPECIES		
Colonial hydroid, *Campanularia flexuosa*	11 days	Growth rate inhibition	10-13	Stebbing, 1976
Colonial hydroid, *Campanularia flexuosa*	-	Enzyme inhibition	1.43	Moore & Stebbing, 1976
Colonial hydroid, *Eirene viridula*	14-21 days	Growth rate inhibition	30-60	Karbe, 1972
Polychaete worm, *Cirriformia spirabracha*	26 days	50% mortality	40	Milanovich, et al. 1976
Polychaete worm, *Phyllodoce maculata*	9 days	50% mortality	80	McLusky & Phillips, 1975
Polychaete worm, *Neanthes arenaceodentata*	28 days	50% mortality	44	Pesch & Morgan, 1978
Polychaete worm, *Neanthes arenaceodentata*	28 days	50% mortality	100	Pesch & Morgan, 1978
Bay scallop, *Argopecten irradians*	42 days	EC50, growth	5.8	U.S. EPA, 1980
Bay scallop, *Argopecten irradians*	119 days	100% mortality	5	U.S. EPA, 1980
American oyster (larva), *Crassostrea virginica*	12 days	50% mortality	46	Calabrese, et al. 1977

Table 6. (Continued)

Species	Duration	Effect	Result (µg/l)	Reference
Black abalone, *Haliotis cracherodii*	4 days	Histopathological gill abnormalities	>32	Martin, et al. 1977
Red abalone, *Haliotis rufescens*	4 days	Histopathological gill abnormalities	>32	Martin, et al. 1977
Northern quahaug (larva) *Mercenaria mercenaria*	8-10 days	50% mortality	30	Calabrese, et al. 1977
Northern quahaug, *Mercenaria mercenaria*	77 days	53% mortality	25	Shuster & Pringle, 1968
Soft shelled clam, *Mya arenaria*	7 days	50% mortality	35	Eisler, 1977
Mussel, *Mytilus edulis*	7 days	50% mortality	200	Scott & Major, 1972
Channeled whelk, *Busycon canaliculatum*	77 days	50% mortality	470	Betzer & Yevich, 1975
Mud snail, *Nassarius obsoletus*	3 days	Decrease in oxygen consumption	100	MacInnes & Thurberg, 1973
Calanoid copepod, *Acartia clausi*	2 days	50% mortality	34-82	Moraitou-Apostolopoulou, 1978
Calanoid copepod, *Acartia tonsa*	6 days	50% mortality	9-73	Sosnowski, et al. 1979
Copepod, *Metridia pacifica*	24 hrs	LC50	176	Reeve, et al. 1976
Copepod, *Phialidaum* sp.	24 hrs	LC50	36	Reeve, et al. 1976
Calanoid copepod, *Acartia tonsa*	24 hrs	LC50	104-311	Reeve, et al. 1976
Copepod, *Euchaeta marina*	24 hrs	LC50	188	Reeve, et al. 1976

Table 6. (Continued)

Species	Duration	Effect	Result (µg/l)	Reference
Copepod, *Undinula vulgaris*	24 hrs	LC50	192	Reeve, et al. 1976
Copepod (nauplii), Mixed species	24 hrs	LC50	90	Reeve, et al. 1976
Rotifer, *Brachionus plicatilis*	24 hrs	LC50	100	Reeve, et al. 1976
Ctenophore, *Mnemiopsis mccrodyi*	24 hrs	LC50	17-29	Reeve, et al. 1976
Ctenophore, *Pleurobrachia pileus*	24 hrs	LC50	33	Reeve, et al. 1976
Larval annelids, Mixed species	24 hrs	LC50	89	Reeve, et al. 1976
Chaetognath, *Sagitta hispida*	24 hrs	LC50	43-460	Reeve, et al. 1976
Shrimp, *Euphausia pacifica*	24 hrs	LC50	14-30	Reeve, et al. 1976
Copepod, *Labidocera scotti*	24 hrs	LC50	132	Reeve, et al. 1976
American lobster, *Homarus americanus*	13 days	50% mortality	56	McLeese, 1974
Coral-reef echinoid, *Echinometra mathaei*	4 days	Suppression of larval skeletal development	20	Heslinga, 1976
Sea urchin, *Arbacia punctulata*	-	58% decrease in sperm motility	300	Young & Nelson, 1974
Sea urchin, *Paracentrotus lividus*	4 days	Retardation of growth of pluteal larvae	10-20	Bougis, 1965
Mummichog, *Fundulus heteroclitus*	21 days	Histopathological lesions	<500	Gardner & La Roche, 1973

Table 6. (Continued)

Species	Duration	Effect	Result (µg/l)	Reference
Mummichog, *Fundulus heteroclitus*	4 days	Enzyme inhibition	600	Jackim, 1973
Atlantic silverside, *Menidia menidia*	4 days	Histopathological lesions	<500	Gardner & LaRoche, 1973
Pacific herring (embryo), *Clupea harengus pallasi*	6 days	Incipient LC50	33	Rice & Harrison, 1978
Pacific herring (larva), *Clupea harengus pallasi*	2 days	Incipient LC50	900	Rice & Harrison, 1978
Atlantic menhaden, *Brevoortia tyrannus*	14 days	50% mortality	610	Engel, et al. 1976
Spot, *Leiostomus xanthurus*	14 days	50% mortality	160	Engel, et al. 1976
Atlantic croaker, *Micropogon undulatus*	14 days	50% mortality	210	Engel, et al. 1976
Pinfish, *Lagodon rhomboides*	14 days	50% mortality	150	Engel, et al. 1976
Plaice, *Pleuronectes platessa*	4 days	50% mortality	750	Saward, et al. 1975
Winter flounder, *Pseudopleuronectes americanus*	14 days	Histopathological lesions	180	Baker, 1969
Alga, *Laminaria hyperboria*	28 days	Growth decrease	50	Hopkins & Kain, 1971

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* Dissolved copper; no other measurement reported

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Mammalian Toxicology and Human Health Effects

INTRODUCTION

Copper is widespread in the earth's crust, and the extensive use of copper and its compounds by man since prehistoric times has added copper to the environment and the ecosystem in highly variable concentrations.

From 1955 to 1958 the annual United States production of recoverable copper was about 900,000 metric tons. By 1975, the production had risen to 1,260,000 metric tons (D'Amico, 1959; U.S. Bur. Mines, 1976). The world trade in refined copper amounted to 2,271,150 metric tons in 1973 (World Metal Statistics, 1974).

Human exposure to copper can occur from water, food, and air, and through direct contact of tissues with items that contain copper. Copper is essential to animal life; consequently, abnormal levels of copper intake can range from levels so low as to induce a nutritional deficiency to levels so high as to be acutely toxic.

EXPOSURE

Ingestion from Water

Water can be a significant source of copper intake depending upon geographical location, the character of the water (i.e., whether it is soft or hard), the temperature of the water, and the degree of exposure to copper-containing conduits.

Schroeder, et al. (1966) place considerable emphasis on drinking water as a source of copper. They reported that the mean values of copper in human livers (56 cases) from Dallas, Denver, and Chicago varied from 410 to 456 μg/g of ash, and that the mean value from Miami was 578 µg/g of ash[1]. The municipal water supplies of these cities each provided relatively hard potable waters with measured hardness ranging from 75 to 125 mg/l. On the other hand, 143 human livers from seven cities with relatively soft waters ranging from 10 to 60 mg/l had mean levels of copper varying from 665 to 816 µg/g of ash. Of the cases from soft water areas, 37.1 percent had hepatic copper of 700 or more µg/g of ash, compared with only 14.3 percent of the samples from the hard water cities. Of the 56 individuals from three cities with the hardest water, only two showed such high values. Unfortunately no studies were made of cities with very hard water.

Schroeder, et al. (1966) suggested that the higher copper levels in residents of cities with soft water might be due to the ability of soft water to corrode copper pipes and fittings, thereby increasing the intake of soluble copper. Another explanation may lie in the ability of calcium or magnesium ions in hard water to suppress the intestinal absorption of copper.

Schroeder, et al. (1966) reported on the progressive increase of copper in water from brook to reservoir to hospital tap, and the considerable copper increment in soft water, compared with hard water, from private homes (Table 1). The authors found that the daily increment of copper ingested from soft water may amount to 10 to 20 percent of dietary intake.

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[1] The values cannot readily be converted to total copper content present in liver on a wet weight basis since they were secured at autopsy. Information regarding the individuals from which samples came was minimal.

TABLE 1

Copper in Water Flowing through Copper Pipes[a,b]

Item	µg/l
Spring water, Brattleboro, Vermont, mountain	1.2[c]
Municipal water, soft, Brattleboro	
Brook, inlet to reservoir	16
Reservoir, lake	55
Water, main end	150
Hospital, at tap	
cold, running 30 min	170
hot, running 30 min	440
cold, standing 12 hr	550
cold, standing 24 hr	730
Spring water, soft, private houses, Brattleboro, Vermont, at tap	
No. 1 from spring, unpiped	2.8[c]
running 30 min	190
cold, standing 24 hr	1,400
hot, standing 24 hr	1,460[c]
No. 2	1,240
No. 3	75
Well water, private houses, Windham County, at tap	
No. 4, hard	36
No. 5, hard	4.4[c]
No. 6, hard	40
No. 7, hard, at well	4[c]
at tap	36[c]
No. 8, soft	278

[a] Source: Schroeder, et al. 1966.

[b] Water from the main was taken after it had passed through the treatment plant at the entrance to hospital supply system, from whence it ran through copper pipes. This water was chlorinated. Spring and well waters were untreated.

[c] By chemical method using diethyldithiocarbamate after evaporating 1 liter water.

Hadjimarkos (1967), on the contrary, suggested that drinking water may be only a minor source of copper. He reported that the mean drinking water concentration of copper is 0.029 mg/l, which could mean a daily intake of 58 µg of copper in water, or 1 to 8 percent of total daily intake if food intake is 3,200 µg of copper per day.

It is probable that the difference in intakes estimated by Schroeder, et al. (1966) and Hadjimarkos (1967) is due to a difference in location. However, it is difficult to pinpoint local copper concentrations in drinking water sources, since the only readily available information on concentrations of copper in stream water is from areas of 10,000 square miles or greater (Kopp and Kroner, 1968; Thornton, et al. 1966).

Robinson, et al. (1973) in New Zealand have suggested that soft water used exclusively from the coldwater tap to make up daily beverages may add as much as 0.4 mg of copper per day per individual, but that if hot water from the same source is used for the same purposes, it would add at least 0.8 mg of copper per day to an individual's intake.

The average concentration of copper in the United States water systems is approximately 134 µg/l [U.S. Department of Health, Education and Welfare (U.S. HEW), 1970]. The highest concentration reported was 8,350 µg/l; a little over 1 percent of the samples exceeded the drinking water standard of 1 mg/l.

The 1 mg/l copper standard was established not because of toxicosis but because of the taste which develops with higher levels of copper in the water (U.S. HEW, 1970). It is most commonly exceeded in soft water that is acidic in nature; however, it is rare that the concentration of copper in drinking water is high enough to affect its taste or to produce toxicosis (McCabe, et al. 1970; Fed. Water Quality Adm., 1968). For this reason, regulatory agencies have not treated copper in public water supplies as a significant problem. In New York City, copper is intentionally added to the water supply to maintain a concentration of 0.059 mg/l in order to control algal growth (Klein, et al. 1974).

Prolonged contact of acidic beverages with copper conduits, such as occurred in earlier models of drink dispensing machines, may produce sufficient copper concentration to cause acute copper toxicosis (see Acute, Subacute, and Chronic Toxicity section); however, because of taste problems, modern equipment does not contain copper conduits.

The national impact of a water-borne contribution of copper is difficult to detect, predict, or evaluate because information is either absent or irretrievable. The current trend for recycling waste (animal wastes, sewage solids and liquids, channel dredging, and industrial waste) to the land offers very real possibilities that imbalances in organisms may unwittingly be created, because such wastes are commonly high in trace element concentration. These trace elements may directly alter crop production and indirectly affect the consumer (Patterson, 1971).

Another source of copper in water is the use of copper sulfate to control algae. Some idea of the distribution of copper sulfate may be gained from the work of Button, et al. (1977), who applied granular copper sulfate to the surface of Hoover Reservoir, Franklin County, Ohio. Soluble and particulate cupric copper concentrations at several depths were measured by atomic absorption spectrophotometry for four days after application. The soluble cupric copper concentration decreased to near baseline values in 2 to 6 hours when 0.2 or 0.4 gms of copper sulfate per square meter were added to the surface. Most of the copper sulfate was dissolved in the first 1.75 meters of water column, and only 2 percent of the total copper sulfate reached the depth of approximately 4.5 meters. A concentration of 0.4 gms of copper per square meter controlled a diatom bloom.

Ingestion from Food

Levels of copper in various foods are given in Table 2. Some foods, such as crustaceans and shellfish (especially oysters), organ meats (especially lamb or beef liver), nuts, dried legumes, dried vine and stone fruits, and cocoa, are particularly rich in copper. The copper content of these items can range from 20 µg/g to as high as 400 µg/g (McCance and Widdowson, 1947; Schroeder, et al. 1966). On an "as-cooked and as-served" basis, calves' liver, oysters, and many species of fish and green vegetables have recently been classed as unusually good sources of copper (more than 100 µg copper/100 kcal).

High levels of copper may also be found in swine because of the practice, common in the United Kingdom and elsewhere, of feeding to swine diets that are high (up to 250 µg/g) in copper in order to increase daily weight gain. Levels of copper in swine liver vary greatly depending on the copper content of the feed. A high copper diet fed continuously until slaughter may produce levels of

TABLE 2

Copper in Foods (Wet Weight)[a]

Item	µg/g	µg/100 calories[b]
Sea food		
Clams, raw	3.33	694
Clams, fresh frozen	0.48	100
Oysters	137.05	27,410
Sardines, canned Portugese	1.12	38
Kipper snacks, Norway, canned	1.70	85
Anchovies, canned Portugese	0.81	27
Pan fish, dried, V.I.	0.58	49
Lobster, frozen	0.51	42
Shrimp, frozen	3.40	297
Mean, excluding oysters	1.49	167
Meat		
Beef liver	11.00	769
Beef kidney	0.42	34
Beef fat	0.83	21
Pork kidney	5.30	441
Pork loin	3.90	130
Pork liver	3.72	260
Lamb kidney	0.95	96
Lamb chops	7.13	381
Chicken leg and wing	1.99	99
Mean	3.92	249
Dairy products		
Egg yolk	2.44	70
Egg white	1.70	460
Dried skimmed milk	2.09	63
Whole milk, dairy 1	0.26	40
Whole milk, dairy 2	0.12	18
Butter, salted	3.92	49
Mean	1.76	117

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[a] Source: Schroeder, et al. 1966

[b] Caloric values of foods from R.A. McCance and E.M. Widdowson, 1947

V.I. - indicates that the sample came from St. Thomas, Virgin Islands.

TABLE 2 (cont.)

Copper in Foods

Item	μg/g	μg/100 calories[b]
Vegetables		
Peas, green	0.45	70
Peas, split, green dry	12.30	410
Peas, green, V.I.	1.14	181
Peas, split, green, V.I.	2.25	75
Lentils	1.41	47
Yam, white, V.I.	0.32	37
Yam, yellow, V.I.	0.41	47
Turnip, white	1.84	1,022
Turnip greens	0.73	663
Beets	0.15	32
Carrots	3.42	1,487
Tomato, V.I.	0.34	143
Pepper, green, No. 1	0.68	453
Pepper, green, No. 2	0.28	187
Pepper, green, V.I.	0.90	600
Pepper, hot, red, V.I.	0.56	-
Cucumber, No. 1	0.07	70
Cucumber, No. 2	0.47	470
Christofine, V.I.	0.18	257
Egg plant, V.I.	0.06	40
Asparagus	0.37	205
Celery	0.31	344
Cabbage	0.70	350
Parsley	0.20	-
Rhubarb	0.34	567
Mushrooms	0.65	929
Mean	1.17	362
Fruits		
Banana, V.I.	0.66	86
Papaya, V.I.	1.06	265
Coconut, V.I.	0.19	100
Coconut seed, V.I.	3.31	-
Apple, MacIntosh	1.39	278
Mean, excluding coconut seed	0.82	182

TABLE 2 (cont.)

Copper in Foods

Item	µg/g	µg/100 calories[b]
Grains and cereals		
Wheat seed	1.09	33
Wheat, whole	2.48	75
Wheat germ	0.15	-
Wheat head, chaff and stalk	0.14	-
Bread, white	0.19	8
Bread, whole wheat	0.63	25
Oats, whole	0.40	10
Corn, No. 1	0.46	13
Corn, No. 2	0.65	19
Rye, No. 1	0.92	27
Rye, No. 2	4.12	123
Rye, dry, flour	4.20	124
Benzene extract	10.82	-
Residue	1.87	-
Barley	3.83	106
Buckwheat	8.21	227
Rice, brown, U.S.	0.47	13
Rice, Japanese, polished	3.04	84
Bengal gram, India, 1	4.23	120
Bengal gram, India, 2	0.56	16
Grapenuts	14.95	415
Millet	2.34	67
Doughnut, cream filled	2.32	66
Mean, excluding grapenuts and extracts	2.02	58

TABLE 2 (cont.)

Copper in Foods

Item	μg/g	μg/100 calories[b]
Oils and fats		
Lard, canned, 1	3.06	34
Lard, canned, 2	2.50	28
Lard, canned, 3	2.13	24
Lecithin, animal	26.38	-
Lecithin, egg	10.52	-
Cod liver oil, Norway	6.80	-
Castor oil, refined	1.70	-
Corn oil	2.21	25
Corn oil margarine	24.70	274
Cottonseed oil	1.26	14
Olive oil	3.20	36
Sunflower oil	5.44	60
Linseed oil, pressed	1.75	19
Peanut oil, pressed	0.83	9
Lecithin, vegetable, pure	5.31	-
Lecithin, soy, 90 percent pure	4.37	-
Lecithin, soy, refined	20.95	-
Mean, excluding lecithins	4.63	58
Nuts		
Hazelnuts	12.80	233
Peanuts	7.83	131
Walnuts	12.70	231
Brazil nut	23.82	370
Pecans	12.64	211
Almonds	14.11	234
Mean	14.82	235
Condiments, spices, etc.		
Garlic, fresh	3.15	-
Garlic powder	0.75	-
Mustard, dry	3.04	-
Pepper, black	20.73	-
Paprika	8.47	-
Chili powder	5.98	-
Thyme, ground	23.58	-
Bay leaves (laurel)	3.68	-
Cloves, whole	8.67	-
Ginger, ground	2.63	-
Ginger, root, V.I.	1.87	-
Caraway seeds	4.31	-
Vinegar, cider	0.76	-
Yeast, dry, active	17.79	-
Molasses	2.21	85
Sugar, refined	0.57	14
Mean	6.76	-

TABLE 2 (cont.)

Copper in Foods

Item	µg/g	µg/100 calories[b]
Beverages		
Gin, domestic	0.03	1
Vermouth, French	0.88	102
Vermouth, Italian	0.38	44
Whiskey, Scotch	0.35	14
Whiskey, Bourbon	0.18	7
Brandy, California	0.45	18
Bitters, Angostura	0.75	-
Wine, domestic, red	0.28	33
Beer, canned	0.38	76
Cola	0.38	100
Grape juice	0.90	136
Orange drink, carbonated	0.20	43
Orange juice, packaged	0.89	234
Coffee, dry, ground	2.35	-
Coffee, infusion	0.22	-
Tea, infusion	0.31	-
Mean, excluding dry coffee	0.44	20
Miscellaneous		
Chocolate bar, Hershey	0.70	18
Ice cream, vanilla	0.29	15
Gelatin, Knox	3.87	148
Purina laboratory chow	15.61	-
Aspirin, Squibb	3.12	-
Saccharin	5.43	-

up to 400 to 600 µg/g in the liver. However, swine will rapidly eliminate copper once it is removed from the diet. Sheep also accumulate copper in direct proportion to the level of copper in the diet, but they eliminate excess copper very poorly [NRC-42, 1974; National Academy of Science (NAS), 1977; Barber, et al. 1978].

Animal and industrial wastes (including sewage solids) commonly yield high concentrations of copper and other trace elements. The current emphasis on recycling these wastes may unintentionally supply excessive amounts of copper and these other elements to the soil. Such recycling could indirectly affect consumers if the yield of crops were reduced or if copper were increased in feed products (NAS, 1977).

The National Academy of Science (1977) noted that the consumption of sheep or swine livers that are high in copper could result in excessive levels of copper, especially in baby foods where the actual amount of copper might exceed the copper requirements of very young children.

Dairy products, white sugar, and honey rarely contain more than 0.5 µg copper/g. The nonleafy vegetables and most fresh fruits and refined cereals generally contain up to 2 µg/g. Cheese (except Emmental), milk, beef, mutton, white and brown bread, and many breakfast cereals (unless they are fortified) are relatively poor sources of copper, i.e., they have less than 50 µg copper/100 kcal [World Health Organization (WHO), 1973].

The refining of cereals for human consumption results in significant losses of copper, although this loss is not so severe as it is for iron, manganese, and zinc. Levels of copper in wheat and wheat products are given in Tables 3 and 4.

TABLE 3

Mineral Content of Known Wheats, the Flours Milled from them and the Products Prepared from the Flours[a,b]

Sample	Number of Samples	Moisture %	Ash %	Copper µg/g
Wheat, common hard	5	11.0	1.87 ± 0.10	5.1 ± 0.5
Flour, Baker's patent	5	13.9	0.49 ± 0.03	1.9 ± 0.2
Bread, sponge-dough	5	36.3	3.39 ± 0.19	2.3 ± 0.3
Bread, continuous-mix	5	35.3	3.42 ± 0.30	2.0 ± 0.2
Wheat, common soft	4	10.6	1.73 ± 0.17	4.5 ± 0.5
Flour, soft patent (cake)[c]	6	11.9	0.42 ± 0.03	1.6 ± 0.3
Cake	6	22.8	2.71 ± 0.11	0.8 ± 0.1
Flour, straight-grade[c]	5	11.4	0.50 ± 0.05	1.6 ± 0.2
Cracker	5	4.9	3.42 ± 0.50	1.6 ± 0.1
Flour, cut-off (cracker)	2	12.6	0.71 ± 0.04	2.6 ± 0.1
Cracker	2	4.5	3.09 ± 0.34	2.4 ± 0.1
Wheat, Durum	2	10.7	2.03 ± 0.01	4.8 ± 0.1
Semolina	2	14.7	0.83 ± 0.01	2.2 ± 0.1
Marcaroni	2	9.6	0.82 ± 0.01	2.5 ± 0.1

[a] Source: Zook, et al. 1970

[b] Mean and standard deviation, dry weight basis.

[c] Includes two flours prepared by air classification.

TABLE 4

Mineral Content of Consumer Products Purchased in Ten Cities[a,b]

Product	Total Samples Collected No.	Producers Sampled Total No.	Producers Sampled Per City Range	Producers Sampled Model City No.	Moisture %	Ash %	Copper µg/g
Cereal-to-be-cooked	24	7	1-3	3	9.5	1.85 ± 0.07	5.3 ± 0.2
Shredded wheat	47	6	4-6	4	8.0	1.87 ± 0.12	6.1 ± 0.4
Wheat flakes	28	3	2-3	3	4.8	3.78 ± 0.17	4.7 ± 0.3
Bread, whole wheat	38	26	2-8	2	37.8	3.87 ± 0.12	5.1 ± 0.5
Bread, white							
Conventional dough	52	37	3-9	4	35.8	3.23 ± 0.12	2.1 ± 0.2
Continuous-mix	29	17	1-4	2	36.7	3.10 ± 0.13	2.3 ± 0.3
Rolls, hamburger	52	34	4-9	4	33.6	2.85 ± 0.08	2.5 ± 0.2
Doughnuts, cake	28	20	1-5	3	21.9	2.61 ± 0.20	1.7 ± 0.2
Biscuit mix	23	8	1-4	2	9.8	4.28 ± 0.26	1.6 ± 0.2
Flour, all-purpose	31	19	3-4	3	12.9	0.56 ± 0.03	1.8 ± 0.2

[a] Source: Zook, et al. 1970

[b] Mean and standard deviation, dry weight basis.

Schroeder, et al. (1966) have suggested that since copper occurs widely in human foods, it is difficult to prepare a diet of natural foods that provides a daily copper intake of less than 2 mg, the level that is considered to be adequate for normal copper metabolism (Adelstein, et al. 1956).

Tompsett (1934) reported that the normal daily intake of copper from food appeared to be 2 to 2.5 mg per day for human subjects. Daniels and Wright (1934) reported an average intake of 1.48 mg copper per day in young children, with a requirement of not less than 0.10 µg/kg of body weight per day.

Most American and western European diets supply adults with 2 to 4 mg of copper per day. This is evident from studies in England, New Zealand, and the United States. Lower estimates have been made for certain Dutch and poorer Scottish diets, while Indian adults consuming rice and wheat diets have been shown to ingest from 4.5 to 5.8 mg of copper per day (Schroeder, et al. 1966).

Scheinberg (1961) has contended that most adult diets supply a substantial excess of copper. Klevay, on the other hand, has suggested on the basis of recent food analyses that the copper content may be less than earlier analyses indicated and has cautioned that United States diets may not be adequate to provide 2 mg of copper per day (Klevay, 1977; Klevay, et al. 1977).

Dr. Walter Mertz in a personal communication reported that in 1978 the analysis of diets of more than 20 individuals employed at the Institute of Nutrition of the U.S. Department of Agriculture, Beltsville, Md., showed that only two approached an intake of 2 mg of copper per day. The diets of these individuals included soft drinks, water, and snacks, suggesting that food subjected to modern processing and preparation methods may be much lower in copper than was supposed based on earlier analyses, and that many individuals eating these foods may be receiving considerably less than the 2 mg of copper per day.

Engel, et al. (1967) conducted studies on young girls which indicated that 2 µg copper/g of diet was adequate for good nutrition. Petering, et al. (1971) mention that the copper content of hair appears to be related to the age of the individual and suggest that the need for copper may differ between the sexes.

Because of the essentiality of copper, the copper balance in newborn infants has been examined (Cavell and Widdowson, 1964). It was noted that breast milk ranged from 0.051 to 0.077 mg/100 ml and that total copper intakes of the babies ranged from 0.065 to 0.1 mg/kg/day. In the first week of life, some infants excreted more copper than was contained in the milk that they consumed. Of 16 babies, 14 were in negative balance.

As a general statement it would appear that, at least in the United States, there is a greater risk of inadequate copper intake than of an excess above requirements.

A bioconcentration factor (BCF) relates the concentration of a chemical in aquatic animals to the concentration in the water in which they live. An appropriate BCF can be used with data concerning food intake to calculate the amount of copper which might be ingested from the consumption of fish and shellfish. Residue data for a variety of inorganic compounds indicate that bioconcentration factors for the edible portion of most aquatic animals is similar, except that for some compounds, bivalve molluscs (clams, oysters, scallops, and mussels) should be considered a separate group. An analysis (U.S. EPA, 1980) of data from a food survey was used to estimate that the per capita consumption of freshwater and estuarine fish and shellfish is 6.5 g/day (Stephan, 1980). The per capita consumption of bivalve molluscs is 0.8 g/day and that of all other freshwater and estuarine fish and shellfish is 5.7 g/day.

A bioconcentration factor of zero was reported for copper in the muscle of bluegill sunfish (Benoit, 1975). Data are available for several species of saltwater molluscs:

Species	BCF	Reference
Bay scallop, _Argopecten irradians_	3,310	Zaroogian, 1978
Bay scallop _Argopecten irradians_	4,160	Zaroogian, 1978
American oyster, _Crassostrea virginica_	28,200	Shuster and Pringle, 1969
American oyster, _Crassostrea virginica_	20,700	Shuster and Pringle, 1969
Northern quahaug, _Mercenaria mercenaria_	88	Shuster and Pringle, 1968
Soft shelled clam, _Mya arenaria_	3,300	Shuster and Pringle, 1968
Mussel, _Mytilus edulis_	208	Zaroogian, 1978
Mussel, _Mytilus edulis_	108	Zaroogian, 1978
Mussel, _Mytilus edulis_	90	Phillips, 1976
Mussel, _Mytilus galloprovincialis_	800	Majori and Petronio, 1973

If the values of zero and 290 are used with the consumption data, the weighted average bioconcentration factor for copper and the edible portion of all freshwater and estuarine aquatic organisms consumed by Americans is calculated to be 36. The geometric means for scallops, oysters, clams, and mussels are 3,708, 24,157, 539, and 200, respectively, and the overall mean is 290.

Inhalation

The principal source of elevated copper levels in air is copper dust generated by copper-processing operations. However, since the economic value of copper encourages its capture from industrial processes, extraneous emissions are reduced. Other possible sources of copper in air may be tobacco smoke and stack emissions of coal-burning power plants.

Copper has not been considered a particularly hazardous industrial substance because the conditions that would produce excessive concentrations of copper dust or mist in a particle size that could be absorbed and generate toxic effects are apparently quite rare. Investigations of Chilean copper miners have shown that liver and serum concentrations of copper are normal, despite years of exposure to copper sulfide and copper oxide dust, both of which are insoluble (Scheinberg and Sternlieb, 1969). However, workers can be exposed to excess concentrations of copper in any of its forms, and when this occurs, undesirable health effects can result. A 24- to 28-hour illness characterized by chills, fever, aching muscles, dryness in the mouth and throat, and headache, has been noted where workers are exposed to metal fumes within closed areas as a result of the welding of copper structures (McCord, 1960).

The U.S. Occupational Safety and Health Administration (OSHA) has adopted standards of exposure to airborne copper at work. The time-weighted average for 8-hour daily exposure to copper dust is limited to 1 mg/m^3 of air. The standard for copper fume was changed in 1975 to 0.2 mg/m^3 (Gleason, 1968; NAS, 1977).

In 1966, a National Air Sampling Network survey showed that the airborne copper concentrations were 0.01 and 0.257 $\mu g/m^3$ in rural and urban communities, respectively (Natl. Air Pollut. Control Admin., 1968). Even near copper smelters, where high levels (1 to 2 $\mu g/m^3$) are reached, the dose of metal that would be acquired through inhalation of ambient air would comprise only about 1 percent of the total normal daily intake (Schroeder, 1970).

Generally speaking, inhalation of copper or copper compounds is of minor significance compared to other sources, e.g., copper in foods, drinking water, and other fluids, and use of copper for medical purposes.

Dermal

Copper toxicity has resulted from the application of copper salts to large areas of burned skin or from introduction of copper into the circulation during hemodialysis. The source of the copper in hemodialysis may be the membranes fabricated with copper, the copper tubing, or the heating coils of the equipment. Copper stopcocks in circuits can also cause potentially hazardous infusions of copper (Holtzman, et al. 1966; Lyle, et al. 1976).

Studies with monkeys indicated that copper used as dental fillings and placed in cavities in the deciduous teeth of the monkey caused more severe pulp damage than any of the other materials studied. This is additional evidence that tissues exposed directly to copper or copper salts will suffer adverse effects due to the direct absorption of the copper by the tissues (Mjor, et al. 1977).

Recent papers from Australia (Walker, 1977; Walker, et al. 1977) suggest the possibility of copper absorption through the skin as a result of perspiration action on the copper bracelet, sometimes worn as treatment for arthritis, although the therapeutic value of this has little support.

Concern has been directed toward the absorption of copper as a result of the use of the intrauterine device (IUD) as a contraceptive measure (NAS, 1977). Analysis of IUDs that have been in utero for months to years shows that about 25 to 30 mg of copper are lost each year. Some of the metal is excreted with endometrial secretions. Experimental evidence to date does not indicate that use of an IUD results in harmful accumulations of copper (see Absorption section for additional information).

PHARMACOKINETICS[2]

Absorption

Tracer studies provide the basis for the conclusions that most absorption in man takes place in the stomach and the duodenum. Copper absorption appears to be regulated by the intestinal mucosa, and maximum copper levels occur in the blood serum within one to three hours after oral intake.

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[2] Acknowledgement is made of the courtesy of the late Dr. Karl E. Mason and Dr. Walter Mertz who allowed the author to read their manuscript, Conspectus on Copper, to be published in the Journal of Nutrition.

Much of the information on copper absorption in humans has come from studies of patients with Wilson's disease. Studies conducted with these patients using radioactive copper indicate that about one-half of the copper in the diet is not absorbed but is excreted directly into the feces. The average absorption in these individuals has been reported to be approximately 40 percent (Sternlieb, 1967; Strickland, et al. 1972a). Investigations by Cartwright and Wintrobe (1964a) indicated that the daily intake of copper in Wilson's disease patients was 2 to 5 mg, of which 0.6 to 1.6 mg were absorbed, 0.5 to 1.2 mg were excreted in the bile, 0.1 to 0.3 mg passed directly into the bowel, and 0.01 to 0.06 mg appeared in the urine.

Information from these studies indicates that absorbed copper is rapidly transported to blood serum and taken up by the liver, from which it is released and incorporated into ceruloplasmin. Any copper remaining in the serum is attached to albumin or amino acids or is used to maintain erythrocyte copper levels (Weber, et al. 1969; Bearn and Kunkel, 1954, 1955; Beckner, et al. 1969; Bush, et al. 1955; Jensen and Kamin, 1957).

Estimates of the amount of the copper that is actually absorbed by normal individuals vary considerably and must be considered inconclusive. The values obtained have ranged from as low as 15 percent to as high as 97 percent (Weber, et al. 1969), although it seems probable that subjects having these extreme values were not in a steady state. The uncertainty of these values is confounded by the lack of accurate information regarding the excretion of copper in its various forms by way of the biliary system. Even less information is available regarding the reabsorption of copper or copper compounds from the intestine after they have been excreted in the bile. Most of the values that have been obtained with normal subjects suggest that 40 to 60 percent of the dietary copper is absorbed (Van Ravensteyn, 1944; Cartwright and Wintrobe, 1964a; Bush, et al. 1955; Matthews, 1954; Weber, et al. 1969; Strickland, et al. 1972a,b; Sternlieb, 1967).

Animal studies have shown that copper is absorbed by at least two mechanisms, an energy-dependent mechanism and an enzymatic mechanism (Crampton, et al. 1965), and that many factors may interfere with copper absorption, including competition for binding sites as with zinc, interactions with molybdenum and with sulphates, chelation with phytates, and the influence of ascorbic acid. Ascorbic acid will aggravate copper deficiency by decreasing copper absorption. In cases of excess copper intake, ascorbic acid can reduce the toxic effects (Gipp, et al. 1974; Hunt, et al. 1970; Voelker and Carlton, 1969).

Studies with laboratory animals have shown that once copper enters the epithelial cells, it is taken up by a cellular protein similar to liver metallothionein (Evans, et al. 1973; Evans, 1973; Starcher, 1969). Absorbed copper is bound to albumin and transported in the plasma. Approximately 80 percent of the absorbed copper is bound in the liver to metallothionein. The remaining copper is incorporated into compounds such as cytochrome-c-oxidase or is sequestered by lysosomes (Bearn and Kunkel, 1954, 1955). Little information is available concerning absorption of copper into the lymphatics, although in pathological conditions this may be significant (Trip, et al. 1969).

Several studies have been conducted on humans and laboratory animals concerning absorption of copper as a result of the use of copper IUDs. Studies with the IUD in rats have suggested that as much as 10 to 20 mg of copper may be absorbed (Oreke, et al. 1972). This amount, which is small compared to the dietary copper usually ingested, may or may not be metabolized and excreted by the same homeostatic mechanisms that operate with ingested copper. If an IUD were used for many decades and the absorbed copper were retained, it would result in amounts of copper similar to those retained from dietary copper by patients with Wilson's disease. Such levels could result in chronic toxicosis.

Japanese investigators (Okuyama, et al. 1977) have compared effects of using the IUD with copper and the IUD without copper in two groups of women, using a third group as controls. Pregnant women with an IUD in place were also examined. No significant difference was found in the endometrial copper levels in the three groups. There was a tendency toward an increase above controls in the endometrial level of copper during the secretory phase in those women using the IUD with or without copper. No significant difference was found between women who had used an IUD more than 13 months and those who had used it less than 13 months. The copper content of the chorion and the decidua of the pregnant women with IUDs in place did not differ from the levels noted in pregnant women without IUDs. Apparently, the long-term use of copper-containing IUDs did not lead to an accumulation of copper in the uterus.

Tamaya, et al. (1978) have studied the effect of the copper IUD on the histology of the endometrium in the proliferative and the secretory phases of women. Their results indicate that the copper IUD affected the secretory endometrium but not the proliferative endometrium.

In another study, Israeli women with the Latex Leaf IUD, which contains both copper and zinc, showed increased levels of both metals if they had had low serum levels of copper and zinc before insertion. However, their copper and zinc levels did not exceed the upper limits of normal values. No significant statistical difference was found between the serum levels of copper before and after insertion of the IUD.

It has been suggested that diabetic women may respond differently from normal healthy women to the use of a copper IUD. In 11 diabetics, the presence of a copper IUD did not increase the fibrolytic activity in the endometrium, although such an effect was observed in nondiabetics. Since there is evidence that enhancement of the endometrial fibrolytic activity prevents adhesion and implantation of ova, the results may explain the report of less reliable contraceptive effect of the IUD in diabetic women (Larsson, et al. 1977).

A number of studies of the effect of copper upon fertility in animals have incidentally measured copper in tissues. Studies of copper beads in rabbits (Quijada, et al. 1978), copper wires inserted into the vas deferens of male rats (Kartar and Chowdhury, 1977), and copper IUDs in rats have all suggested that copper does have some influence on hormone secretion and tissue copper levels in the reproductive tract; however, these experiments do not present any evidence for accumulation of copper as a result of the use of IUDs (Murakimi, et al. 1978).

Distribution

The amount and distribution of copper in body tissues varies with sex, age, and the amount of copper in the diet. Copper content of fat-free tissues of most animals ranges upward from about 2 µg/g. The highest concentrations of copper in both animal and human tissues are found in the liver and the brain, with lesser amounts in the heart, the spleen, the kidneys, and blood (Cartwright and Wintrobe, 1964a,b; Smith, 1967; Schroeder, et al. 1966). Some tissues are very high in copper, e.g., the iris and the choroid of the eye, which may contain as much as 100 µg/gm (Bowness and Morton, 1952; Bowness, et al. 1952).

Estimates of the total amount of copper in a 70 kg man have ranged from 70 to 120 mg. Approximately one-third of body copper is found in the liver and the brain, one-third is found in the musculature, and the remaining one-third is dispersed in other tissues. It has been estimated that, on the average, about 15 percent of the total body copper is contained in the liver (Tipton and Cook, 1963; Sumino, et al. 1975; Sass-Kortsak and Bearn, 1978). The relatively high percentage of liver copper is related to the liver's function as a storage organ for copper and as the only site for the synthesis and release of ceruloplasmin, the most abundant copper protein in the blood.

In the brain, the striatum and both components of the cortex (gray matter) have the highest copper content, with the cerebellum (white matter) being the lowest (Hui, et al. 1977; Cumings, 1948; Earl, 1961). The brain appears to be the only tissue in which there is a consistent increase in copper content with age. Other tissues appear to be under a homeostatic control.

Copper levels in hair vary widely with respect to age, sex, and other factors, and therefore have little meaningfulness in evaluating copper levels in man (Underwood, 1977). However, Jacob, et al. (1978) have suggested that the copper in hair may be useful in evaluating the total liver content of copper. Engel, et al. (1967) surveyed over 180 adolescent girls in the 6th to 8th grades for dietary intake and nutritional status. They found that the mean concentration of copper in hair samples was 31 ± 23 µg/g. No significant difference was found between girls who had experienced menarche and those who had not.

Levels of copper in the blood of normal adults average 103 µg/100 ml of blood. The amount of copper in blood serum can range widely from 5 µg/100 ml to 130 µg/100 ml. In practically all species, copper deficiency is first manifested by a slow depletion of body copper stores, including the blood plasma, eventually resulting in a severe anemia identical to that caused by iron deficiency (Cartwright, et al. 1956).

Both the plasma and the erythrocytes have two pools of copper, a labile pool and a stable pool, which contain approximately 40 and 60 percent respectively, of the copper in the blood (Bush, et al. 1955). Ceruloplasmin represents the predominant portion of copper in the serum pool. There appears to be little or no interchange between ceruloplasmin copper and other forms of copper in the blood stream (Sternlieb, et al. 1961). Mondorf, et al. (1971) indicate that the blood contains an average of 30 µg of ceruloplasmin/100 ml of blood. This is in reasonable accord with accepted levels of copper in the blood of normal adults (approximately 103 µg total copper/100 ml of blood). White blood cells contain a small amount of copper, about one-fourth the concentration in erythrocytes (Cartwright, 1950).

The distribution of copper in the fetus and in infants is quite different from that in the adult. The percentage of copper in the body increases progressively during fetal life (Shaw, 1973). Chez, et al. (1978) found that concentrations of copper in amniotic fluid increased between the 26th and 33rd weeks of pregnancy, but that there did not appear to be a correlation between maternal and fetal copper concentrations.

At birth, the liver and spleen contain about one-half the copper of the whole body (Widdowson and Spray, 1951). A newborn infant contains about 4 mg/kg as compared to approximately 1.4 mg/kg in the 70 kg man (Widdowson and Dickerson, 1964). The liver of the newborn has approximately 6 to 10 times the amount of copper in the liver of an adult man on a per gram basis (Bruckmann and Zondek, 1939; Nusbaum and Zettner, 1973; Widdowson, et al. 1951).

The concentration of copper in the serum of newborn infants is significantly lower than in 6- to 12-year-old healthy children, but by five months of age the serum concentration of copper is approximately the same as in older children. There is no difference between copper levels in male and female infants, although breast-fed infants seem to have somewhat higher copper levels by one month than bottle-fed infants (Ohtake, 1977). The liver copper content of the fetus is several times higher than maternal liver copper (Seeling, et al. 1977).

Metabolism

The copper content of red blood cells remains remarkedly constant, but the plasma copper is subject to striking changes associated with the synthesis and release of ceruloplasmin, which is the most abundant copper protein that responds to deficiencies or excesses (Gubler, et al. 1953; Lahey, et al. 1953).

Some 20 mammalian copper proteins have been isolated, but at least three are identical and others have more than one name. Most of this information has come from animal studies, and its applicability to humans is uncertain. Evans (1973) and others have reviewed this subject (Mann and Keilin, 1938; Osborn, et al. 1963; Morell, et al. 1961; Sternlieb, et al. 1962).

Copper plasma levels during pregnancy may be two to three times the normal nonpregnant level. This is almost entirely due to the increased synthesis of ceruloplasmin (Henkin, et al. 1971; Markowitz, et al. 1955; Scheinberg, et al. 1954). The source of this copper appears to be the maternal liver. The increase in maternal plasma copper levels appears to be associated with estrogen, since either sex receiving estrogen shows an increase in copper level of the plasma (Elsner and Hornykiewicz, 1954; Gault, et al. 1966; Humoller, et al. 1960; Russ and Raymunt, 1956).

The use of oral contraceptives causes a marked increase in serum copper levels that may be greater than those observed during pregnancy (Oster and Salgo, 1977; Smith and Brown, 1976; Tatum, 1974).

Infant levels of serum copper are low at birth but promptly increase due to the synthesis of ceruloplasmin by the infant's liver (Henkin, et al. 1973; Schorr, et al. 1958).

There are two inherited diseases that represent abnormal copper metabolism, Menkes' disease and Wilson's disease. Menkes' disease is a progressive brain disease caused by an inherited sex-linked recessive trait. It is often referred to as the "kinky hair" disease or "steely hair" disease (Danks, et al. 1972). The primary characteristic of Menkes' disease appears to be a diminished ability to transfer copper across the absorptive cells of the intestinal mucosa (Danks, et al. 1972, 1973). The general symptoms of the disease are similar to those observed in animals suffering from copper deficiency (Oakes, et al. 1976). The prospects for more effective therapeutic measures as a result of early diagnosis appear to be limited.

Wilson's disease, which has also been designated "hepatolenticular degeneration," is caused by an autosomal recessive trait (Bearn, 1953). The disease is actually a copper toxicosis with abnormally high levels of copper in the liver and brain (Cumings, 1948). Symptoms include increased urinary excretion of copper (Spillane, et al. 1952; Porter, 1951), low serum copper levels due to low ceruloplasmin (Scheinberg and Gitlin, 1952), decreased intestinal excretion of copper, and occurrence of Kayser-Fleischer rings due to excessive accumulation of copper around the cornea. If therapy with d-penicillamine is instituted during the early phases of Wilson's disease, it can assure a normal life expectancy, especially when accompanied by a low-copper diet (Deiss, et al. 1971; Sternlieb and Scheinberg, 1964, 1968; Walshe, 1956).

Other abnormalities of copper metabolism are primarily associated with low levels of copper. Hypocupremia, which is defined as

80 μg or less of copper/100 ml (Cartwright and Wintrobe, 1964a), usually refers to a low ceruloplasmin level. In most cases it is probably due to a dietary deficiency of copper or to a failure to synthesize the apoenzyme of ceruloplasmin (Kleinbaum, 1963). Hypocupremia can also result from malabsorption that occurs during a small bowel disease (Sternlieb and Janowitz, 1964).

Hypercupremia, abnormally high levels of copper, occurs with a number of neoplasms (Delves, et al. 1973; Herring, et al. 1960; Goodman, et al. 1967; Janes, et al. 1972). Elevated serum copper levels occur in psoriasis (Kekki, et al. 1966; Molokhia and Portnoy, 1970).

It is well recognized that copper is necessary for the utilization of iron. Much of this work has been done in animals, and the subject is well covered by Underwood (1977). It appears that ceruloplasmin is essential for the movement of iron from cells to plasma (Osaki, et al. 1966). Reticulocytes from copper-deficient animals can neither pick up iron from transferrin normally nor synthesize heme from ferric iron and protoporphyrin at the normal rate (Williams, et al. 1973).

The ratio of copper to other dietary components, e.g., zinc, iron, sulfate, and molybdenum, may be almost as important as the actual level of copper in the diet in influencing the metabolic response of mammalian species (Smith and Larson, 1946). The cardiovascular disorder "falling disease", reported by Bennetts, et al. (1942), is associated with a copper deficiency in cattle. Similar conditions have been observed in pigs and chickens (O'Dell, et al. 1961; Shields, et al. 1961). In this disorder the elastic tissue of major blood vessels is deranged, markedly reducing the tensile strength of the aorta. This appears to be associated with a biochemical lesion, the reduced activity of lysyl oxidase, a copper-requiring enzyme necessary for elastic tissue formation and maintenance (Hill, et al. 1967).

Evans has discussed the metabolic disorders of copper metabolism including nutritional disorders, inborn order errors of proper homeostasis, and disorders due to the lack of copper-requiring enzymes (Evans, 1977).

Particular attention has been given to the role of copper as associated with cardiovascular diseases (Vallee, 1952; Adelstein, et al. 1956). More recently there has been considerable interest in the role of copper and its ratio to zinc as a factor in the level of cholesterol and cholesterol metabolism as it may relate to ischemic heart disease (Klevay, 1977). It has been suggested that a low copper-high zinc ratio may result in an increased level of cholesterol, particularly that part of the blood cholesterol in the serum low density lipoprotein which has been associated with increased susceptibility to ischemic heart disease (Allen and Klevay, 1978a,b; Petering, 1974; Lei, 1978; Klevay, et al. 1977). In a different context, Harman (1970) has suggested that copper in the diet in excess of needs may result in free radicals that cause adverse effects in the cardiovascular system.

Excretion

It has been noted that perhaps 40 percent of dietary copper is actually absorbed (Cartwright and Wintrobe, 1964a). These estimates are largely based on the difference between oral intake and fecal excretion. Urinary excretion of copper plays a very minor role. The fecal excretion represents unabsorbed dietary copper and the copper that is excreted by the biliary tract, the salivary glands, and the gastric and intestinal mucosae (Gollan and Deller, 1973). It should be noted that some of the excreted copper is reabsorbed in the course of its movement down the intestinal tract. Some loss of copper may occur by way of sweat and in the female menses.

One of the principal routes of excretion is by way of the bile; however, because of the difficulty in studying biliary excretion in normal subjects, the evidence for quantitative values of copper excretion by this route is fragmentary. Cartwright and Wintrobe (1964a) suggest that 0.5 to 1.2 mg per day is excreted in the bile. This is in reasonable accord with the report (Frommer, 1974) that excretion was approximately 1.2 mg/day in ten control subjects. It is possible that very little of the copper excreted in the bile is reabsorbed (Lewis, 1973).

Some copper (approximately 0.38 to 0.47 mg/day) is excreted in the saliva, but there is little evidence as to whether this copper is or is not absorbed in the intestine (DeJorge, et al. 1964).

It is possible that the gastric secretion of copper approximates 1 mg of copper per day, but there is very little published information on this subject (Gollan, 1975).

The amount of copper excreted in the urine is small. Estimates range from 10 to 60 μg/day and average 18 μg/day (Cartwright and Wintrobe, 1964a; Zak, 1958). It is possible, of course, that copper may be reabsorbed from the kidney tubules (Davidson, et al. 1974).

Studies in New Zealand conducted on young women with a copper intake of 1.8 to 2.09 mg/day showed an excretion in the feces of between 65 and 94 percent of the intake. The urinary excretion amounted to 1.7 to 2.2 percent of the intake (Robinson, et al. 1973).

Under some conditions a considerable amount of copper may be lost through sweat, perhaps as much as 1.6 mg of copper per day or about 45 percent of the total dietary intake (Consolazio, et al. 1964).

There is very little information on the loss of copper by way of the menstrual flow, but an average value of 0.11 ± 0.07 mg per period seems reasonable (Ohlson and Daum, 1935; Leverton and Binkley, 1944).

Sternlieb, et al. (1973) note that 0.5 to 1.0 mg of copper is catabolized daily by the adult liver, and about 30 mg of ceruloplasmin, which contains 0.3 percent copper, is excreted into the intestine (Waldmann, et al. 1967). The copper excreted into the intestine in the bile may not be readily available for reabsorption because it is bound to protein; the copper found in the feces seems to come from various secretions, as well as the copper that is not absorbed from food (Gollan and Deller, 1973).

In summary it may be said that most copper is excreted by way of the biliary system with additional amounts in sweat, urine, saliva, gastric and intestinal mucosae, and menstrual discharge.

Examination of the pharmokinetic data points up the fact that the biological half-life of copper is very short. This provides significant protection against accumulations of copper even with intakes considerably above levels considered adequate.

EFFECTS

Acute, Subacute, and Chronic Toxicity

Copper toxicity produces a metallic taste in the mouth, nausea, vomiting, epigastric pain, diarrhea, and depending on the severity, jaundice, hemolysis, hemoglobinuria, hematuria, and oliguria. The stool and saliva may appear green or blue. In severe cases anuria, hypotension, and coma can occur.

Toxic levels of copper ingested are promptly absorbed from the upper gut, and the copper level in the blood is rapidly increased, primarily because of its accumulation in the blood cells. Hemolysis occurs at high copper levels. A high level in the blood can also result from absorption through the denuded skin, as when applied to burns, because of dialysis procedures, or because of exchange transfusions. The hemolysis is due to the sudden release of copper into the blood stream from the liver that has been damaged by an increasing load of copper and is unable to utilize the copper in the synthesis of ceruloplasmin, which in turn can be excreted by way of the biliary system (Chuttani, et al. 1965; Bremner, 1974; Cohen, 1974; Deiss, et al. 1970; Roberts, 1956; Bloomfield, et al. 1971; Ivanovich, et. al. 1969; Bloomfield, 1969).

Chatterji and Ganguly (1950) describe a nonfatal type of copper poisoning in which the symptoms are laryngitis, bronchitis, intestinal colic with catarrh, diarrhea, general emaciation, and anemia.

Burch, et al. (1975) have estimated that the toxic intake level of inorganic copper for an adult man is greater than 15 mg per dose. The vomiting and diarrhea induced by ingesting small quantities of ionic copper generally protect the patient from the serious systemic toxic effects which include hemolysis, hepatic necrosis, gastrointestinal bleeding, oliguria, azotemia, hemoglobinuria, hematuria, proteinuria, hypotension, tachycardia, convulsions, or death (Chuttani, et al. 1965; Davenport, 1953).

Because most of the information about acute copper toxicity in humans has come from attempts at suicide or from the accidental intake of large quantities of copper salts, the information about the changes occurring with acute toxicity are meager.

Acute copper poisoning does occur in man when several grams of copper sulfate are eaten with acidic food or beverages such as vinegar, carbonated beverages, or citrus juices (Walsh, et al. 1977). Some cases of acute poisoning have occurred when tablets containing copper sulfate were given to children (Forbes, 1947).

When carbonated water remains in copper check valves or drink-dispensing machines overnight, the copper content of the first drink of the day may be increased enough to cause a metallic taste, nausea, vomiting, epigastric burning, and diarrhea (Hooper and Adams, 1958). Drinks that are stored in copper-lined cocktail shakers or vessels can have the same effect (Pennsylvania Morbidity and Mortality Weekly Reports, 1975; McMullen, 1971).

Salmon and Wright (1971) have reported the possibility of chronic copper poisoning as a result of water moving through copper pipes. They document a case in which a family moved into a house in North London with a hot water system entirely composed of copper. The water was stored in a 40-gallon copper tank which reached a temperature of 93°C at night. The family used hot water for all cooking and beverages. After two months, the electric kettle was coated inside with a thick green film of the copper complex. The child in the family was admitted to the hospital after five weeks of behavior change, diarrhea, and progressive marasmus. When it was first seen, the clinical picture was that of "pink" disease with prostration, misery, red extremities, hypotonia, photophobia, and peripheral edema. The liver was palpable 2 cm below the costal margin. The serum copper level was 286 μg/100 ml, compared to a normal range of 164 ± 70 μg/100 ml. Analysis of water in the home found 350 μg/l of copper in the cold water and 790 μg/l of copper in the hot water. Cold and hot water levels in the hospital were 40 and 300 μg/l, respectively, and in North London the values were 80 and 160 μg/l.

Walker-Smith and Blomfield (1973) treated the male infant described in the preceeding paragraph, who had received high levels of copper from contaminated water over a period of three months, with d-penicillamine and prednisolone. The infant made a slow recovery. The method of Eden and Green (1940) was used to determine copper levels. It is possible that the infant was exhibiting Wilson's disease and responded to the appropriate treatment.

Eden and Green (1940) reported on a male infant who received high levels of copper from contaminated water ingested over a period of three months. The result was chronic copper poisoning. Treated with d-penicilliamine and prednisolone, the infant made a slow recovery.

In general, however, the problems associated with high levels of copper in drinking water are more or less controlled because of

(1) taste (since high levels of copper in water produce a metallic taste), and (2) cosmetic considerations (since water with high copper content develops a surface scum due to the formation of insoluble copper compounds).

Chronic toxicity has been studied in animals, and there appears to be a wide variation in the tolerance of different species for high levels of copper in the diet. Sheep are very susceptible to high copper intakes, whereas rats have been shown to be very resistant to the development of copper toxicity.

Swine will develop copper poisoning at levels of 250 μg of copper/g of diet unless zinc and iron levels are increased. Suttle and Mills (1966) have studied dietary copper levels ranging up to 750 μg/g in the diet of swine. Toxicosis does develop with hypochromic microcytic anemia, jaundice, and marked increases in the liver and serum copper levels as well as serum aspartate amino transferase. These signs of copper toxicosis in swine can be eliminated by including an additional 150 μg of zinc and iron/g in diets containing up to 450 μg of copper/g; the addition of even more zinc and iron, 500 to 750 μg/g, will overcome the effects of 750 μg of copper/g of diet.

Chronic oral intake of copper acetate in swine and rats can produce a condition comparable to hepatic hemosiderosis in man (Mallory and Parker, 1931). Some question exists as to whether hemosiderosis in man is a result of copper toxicity, because people consuming comparatively high levels of copper do not develop this condition regularly.

Sheep are quite susceptible to high levels of copper in the diet. Copper levels of 35 μg/g of feed have resulted in toxicity when fed over a period of nine months to one year (Fontenot, et al. 1972). Cattle are much more resistant to copper in the diet; 2 g of copper sulfate given daily did not produce toxic reactions (Cunningham, 1931).

It is well known that with ruminant animals, molybdenum and sulfate interact with the copper. Copper toxicity is counteracted by inclusion of molybdenum and sulfate in the diet of ruminants (Dick, 1953; Kline, et al. 1971; Wahal, et al. 1965).

Synergism and Antagonism

There is some evidence that copper may increase the mutagenic activity of other compounds. Using strain TA100 of Salmonella typhimurium, Omura, et al. (1978) studied the mutagenic actions of triose reductone and ascorbic acid. They found that the addition of the copper to triose reductone at a ratio of 1:1,000 lowered the most active concentration of the triose reductone to 1 mM from 2.5 to 5 mM.

Another enediol reductone, asborbic acid, had no detectable mutagenic action by itself, but a freshly mixed solution of 5 mM of ascorbic acid and 1 or 5 μM of cupric copper had an effective mutagenic action. Ascorbyl-3-phosphate had no mutagenic function even in the presence of cupric copper. The investigators suggested that it was the enediol structure in the reductones that was the essential for mutagenicity.

In the Acute, Subacute, and Chronic Toxicity section, it was pointed out that the dietary levels of zinc and iron are as important as the level of copper in determining the toxic level of copper.

Teratogenicity

There is very little evidence in the literature to suggest that copper has a teratogenic effect in either animals or humans.

Mutagenicity

No data were found to suggest that copper itself has a mutagenic effect in either animals or humans; however, one report exists suggesting that copper may increase the mutagenic activity of other compounds (see Synergism and Antagonism section).

Carcinogenicity

There is very little evidence in the literature to suggest that copper has a carcinogenic effect in either animals or humans. Pimental and Marques (1969) noted that vineyard workers in France, Portugal, and southern Italy, exposed to copper sulfate sprays mixed with lime to control mildew, developed granulomas in the liver and malignant tumors in the lung (Pimental and Menezes, 1975; Villar, 1974). Because of the route of exposure, quantitative estimates are, at best, speculative.

It has been noted earlier that the conditions in industry that would produce excessive concentrations of copper as a dust or a mist with particle sizes that would result in toxic effects if the copper were absorbed, are apparently quite rare. Some investigators have suggested that lung cancer, which is prevalent in copper smelter workers, is actually due to the arsenic trioxide in the dust and that the copper itself did not play any etiologic role in the development of the cancer (Kuratsune, et al. 1974; Lee and

Fraumeni, 1969; Milham and Strong, 1974; Tokudome and Kuratsune, 1976).

Some studies have reported that, with the development of various tumors, the copper content in both blood and the tumor tissue is likely to increase, although this is not always the case (Pedrero and Kozelka, 1951; Dick, 1953; Kline, et al. 1971; Wahal, et al. 1965). However, when an increase occurs, it appears to be a result of an inflammatory response or stress rather than any direct causative relationship.

Polish workers (Legutko, 1977) have suggested that the copper level of the serum is a particularly sensitive indicator of the clinical condition and effectiveness of treatment of lymphoblastic leukemia in children, but again no particular relationship to the development of the leukemia is indicated.

Russian scientists (Bezruchko, 1976) have also studied the copper and ceruloplasmin in patients with cancer and noted that the levels of both ceruloplasmin and copper were increased in metastatic cancer of the mammary gland, in skin melanoma, and in ovarian cancer. The serum levels of ceruloplasmin increased 27, 20, and 44 percent, respectively, for those tumors, and the copper increased by 41, 35, and 51 percent, respectively, for those same tumors as compared with normal tissue. Again, no correlation was found between the tumor and copper as a causative agent.

Workers in Hong Kong (Fong, et al. 1977) have been investigating copper concentrations in cases of esophageal cancer in both humans and animals. They report that serum copper is increased slightly and that this is paralleled by a decrease in zinc content.

In summary, it must be stated that evidence for the oncological effects of copper, even at high concentrations, is essentially nonexistent. With the exception of the references cited, there appear to be no definitive reports of copper as a causative agent in the development of cancer. There is much more evidence that a deficiency of copper will have adverse effects both in animals and in humans due to its essential role in the functioning of many enzyme systems.

CRITERION FORMULATION

Existing Guidelines and Standards

Far more attention has been given to the problems of copper deficiency than to the problems of excess copper in the environment. The 1 mg/l standard that has been established for copper levels in water for human consumption has been adopted more for organoleptic reasons rather than because of any evidence of toxic levels (Fed. Water Quality Admin., 1968).

Cohen, et al. (1960) noted that various investigators have reported adverse taste of water containing 3 to 5 mg/l, 2 mg/l and 1.5 mg/l of copper. The choice of 1 ppm as a level that was organoleptically satisfactory and below any values of health concern for humans was therefore considered reasonable. This study was used as a basis for the current drinking water standard.

The U.S. Occupational Safety and Health Administration has adopted standards for exposure to airborne copper at work. The time-weighted average for 8-hour daily exposure to copper dust is limited to 1 mg/m^3 of air. The standard for copper fume was changed in 1975 to 0.2 mg/m^3 (Gleason, 1968; Cohen, 1974).

As indicated below, the Food and Nutrition Board of the National Academy of Sciences (1980) recommends a daily allowance of 0.5 to 1.0 mg/day for infants, 1.0 to 2.0 mg/day for pre-schoolers, 2.0 to 2.5 mg/day for older children, and 2.0 to 3.0 mg/day for teenagers and adults.

Age (yrs)	RDA (mg/day)	Age (yrs)	RDA (mg/day)
0.0-0.5	0.5-0.7	4- 6	1.5-2.0
0.5-1.0	0.7-1.0	7-10	2.0-2.5
1-3	1.0-1.5	11-Adult	2.0-3.0

There are no standards for copper in medical practice such as the treatment of burns or dialysis or for parenteral feeding.

Current Levels of Exposure

As has been mentioned earlier, principal concern has been for conditions of copper deficiency rather than copper toxicity. It has been suggested earlier that copper intakes in food and water may range from 6 to 8 mg per day, and that the percentage absorbed varies with the nutritional status. On the other hand, because of changes in food processing and, perhaps, because of better methods of analysis, copper intakes may not reach the 2 mg per day considered an adequate nutritional intake (Klevay, et al. 1977; Diem and Lentner, 1970; Robinson, et al. 1973; Schroeder, et al. 1966; WHO, 1973; Cartwright and Wintrobe, 1964a).

The average concentration of copper in United States water systems is approximately 134 μg/l with a little over 1 percent of the samples taken exceeding the drinking water standard of 1 mg/l (McCabe, et al. 1970). When the U.S. Public Health Service studied urban water supply systems, they found that only 11 of 969 systems had copper concentrations greater than 1 mg/l (U.S. HEW, 1970).

In 1966, the National Air Sampling Network found airborne copper concentrations ranging from 0.01 to 0.257 $\mu g/m^3$ in rural and in urban communities, respectively. Levels of copper as high as 1 to 2 $\mu g/m^3$ were found near copper smelters, but this was not considered hazardous (Natl. Air Pollut. Control Admin., 1968; Schroeder, 1970).

Special Groups at Risk

Increased copper exposure, with associated health effects, has occasionally occurred in young children subjected to unusually high concentrations of copper in soft or treated water that has been held in copper pipes or stored in copper vessels. Discarding the first water coming from the tap can reduce this hazard. Similar problems have developed in vending machines with copper-containing conduits where acid materials in contact with the copper for periods of time have dissolved copper into the vended liquids.

Other groups that may be at risk are medical patients suffering from Wilson's disease and those patients who are being treated with copper-contaminated fluids in dialysis or by means of parenteral alimentation. These are medical instances in which the copper content of the materials used should be carefully controlled.

There is also a reasonable likelihood that exposure to elevated levels of copper (ca. 1.0 ppm) from community drinking water may be a contributory factor in the precipitation of acute hemolysis in individuals with a glucose-6-phosphate dehydrogenase (G-6-PD) deficiency. Approximately 13 percent of the American black male population has a G-6-PD deficiency (Beutler, 1972). G-6-PD deficient humans were found to be markedly more sensitive to several indicators of oxidant stress as measured by increases in methemoglobin levels and decreases in the activity of red cell acetylcholinesterase indicating that susceptibility to copper-induced oxidative stress is associated with the presence of low red cell G-6-PD activity (Calabrese and Moore, 1979; Calabrese, et al. 1980).

A final group that may be subject to risk of copper toxicity consists of those people occupationally exposed to copper, e.g., industrial or farm workers.

In reviewing the medical and biologic effects of environmental pollutants, the National Academy of Science (1977) pointed out that use of livers from animals fed high levels of copper in the diet could produce a baby food product that was excessively high in copper. The Committee also raised the question of exposure to copper from intrauterine contraceptive devices (IUDs), but subsequent reports have failed to demonstrate any abnormal accumulation of copper because of the use of these devices.

Basis and Derivation of Criterion

Copper is an essential dietary element for humans and animals. A level of 2 mg per day will maintain adults in balance (Adelstein, et al. 1956) and has been considered adequate, although because of interactions with other dietary constituents that limit absorption and utilization, a requirement level must be considered in conjunction with such constituents as zinc, iron, and ascorbic acid. The minimum level meeting requirements for copper intake in intravenous feeding is 22 µg copper/kg body weight (Vilter, et al. 1974).

The short biological half-life of copper and the homeostasis that exists in humans prevents copper from accumulating, even with dietary intakes considerably in excess of 2 mg per day. In the opinion of many investigators, there is much more likelihood of a copper deficiency occurring than of a toxicity developing with current dietary and environmental situations.

Although acute and chronic levels of intake may occur, there are no data that adequately define these levels. It has been suggested that intakes above 15 mg of copper per day may produce observable effects, but if zinc and iron intakes are also increased, much higher levels may be consumed without adverse reactions. The data for acute toxicity are even more uncertain, since practically all human information stems from cases of attempted suicide.

The available literature leads to the conclusion that copper does not produce teratogenic, mutagenic, or carcinogenic effects. The limited information available indicates that where such action has occurred, e.g., with mixtures of copper sulfate and lime, arsenic, or enediols, the copper should be considered as interacting with the other materials and not as the active material.

The current drinking water standard of 1 mg/l is considered to be below any minimum hazard level, even for special groups at risk such as very young children, and therefore it is reasonable that this level be maintained as a water quality criterion.

Since the current standard and hence the water quality criterion of 1.0 mg/l are based on organoleptic effects (U.S. HEW, 1970) and are not toxicological assessments, the consumption of fish and shellfish is not considered as a route of exposure.

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